AUDITING OF FLUVIAL GEOMORPHOLOGICAL PROCESSES FOR FLOOD DEFENCE IN THE U.K. ENVIRONMENT AGENCY

Jim Walker

University of Southampton, Dept. of Geography

A thesis submitted for the qualification of:
Master of Philosophy

June, 2001

UNIVERSITY OF SOUTHAMPTON

AUDITING OF FLUVIAL GEOMORPHOLOGICAL PROCESSES FOR FLOOD DEFENCE IN THE U.K. ENVIRONMENT AGENCY

Jim Walker, B.Sc. (Hons), M.Sc., AMIES.

A thesis submitted for the qualification of:

Master of Philosophy

FACULTY OF SCIENCE

DEPARTMENT OF GEOGRAPHY

June, 2001

Abstract

This study reviews existing methods of geomorphological and engineering science / practice, with reference to flood defence application in general, and particularly in the U.K. Environment Agency. A new method of geomorphological audit is then developed for application to flood defence maintenance in two case studies covering: the Shelf Brook, (which drains a small upland catchment near Glossop, Derbyshire), and the upper Mersey river system, (which drains a large part of the southern Pennines and northern Peak District).

The global objectives of this exercise were to develop a method of rapid geomorphological catchment appraisal that was versatile and utilitarian. Versatility was defined in terms of, applicability to different physical habitats, catchment sizes, flood defence management objectives and flood defence scheme 'life-stages' (from feasility to post-project appraisal). Utility was defined as the demonstration of the audit's advantages over existing methods, the investigation of any additional data requirements for flood defence application (outside that collected by the audit), and the assessment of the tangibile benefits of the method verses its costs.

Additionally a two year dataset of field geomorphological data were compiled to verify the findings of the audit as part of the first case study. This first study satisfied the global objectives in part, however, in reviewing the application of the audit methods a number of interim areas for expansion were also identified. These comprised: the need to apply the audit methods to a full catchment system of watercourses, the need to include areas of modified channel within the audit to make it more widely applicable, and the importance of looking at inter-observer variability. The question as to whether or not it was possible to reduce the coverage of an audit from 100% of catchment reaches to a sample of the total 'population' of reaches was raised. Additionally, the need to collect more data on the types of erosion and deposition occurring, and the causes of that erosion and deposition, was also identified.

The second case study went on to address these expansion areas, in addition to the original global objectives. Conclusions were then drawn on the overall success of the audit methods developed through these two studies.

Table of Contents

List of Tables

Chapter 1

Chapter 2

Chapter 3

Chapter 4

Chapter 5

List of Figures

Chapter 1

Chapter 2

Chapter 3

Chapter 4

Acknowledgements

My wholehearted thanks are extended to the following, without whose assistance over the last five years I would not have been able to complete this thesis:

Dr. David Sear for his supervision, advice and support, and the University of Southampton in general for the opportunity to undertake this research and for the funding they have contributed, and the Department of Geography in particular, for their assistance and guidance.

The Environment Agency, for their funding and support, and in particular, Steve Crowe as industrial sponser, Peter Spencer as understanding line-manager, and the rest of the Northwest region River Modelling Team for their comradeship and support. Also to Marc Naura for advice and assistance concerning the River Habitat Survey.

All the friends and family who have helped me with field work over the years.

My partner Katy Barker for 'super-human' efforts in the fields of support and understanding.

Preface

A thought from the Tao Te Ching:

The sage's way Tao is the way of water.
There must be water for life to be, and it can flow wherever.
And water being true to being water is true to Tao.

Those on the way of Tao,
like water need to accept where they find themselves;
And that they may often be where water goes to the lowest places,
and that is right.

Like a lake the heart must be calm and quiet,
having great depth beneath it.

The sage rules with compassion,
and his words need to be trusted.
The sage needs to know like water how to flow around blocks,
And how to find the way through without violence.
Like water, the sage should wait for the moment to ripen and be right:
Water, you know, never fights, it flows around without harm.

Tao Te Ching: The New Translation, Man-Ho Kwok, Martin Palmer and Jay Ramsay, Element Books, Dorset.

Chaper 1: Introduction and Literature Review

1.1 'The Big Picture' – This Research Project, Integrated River Basin Management and the Environment Agency.

Since its formation in 1996 the Environment Agency has sought to promote the ideals of integrated river basin management, (i.e. the consideration of differing needs and interests holistically, using the hydrological catchment as the fundimental management unit). Indeed the very formation of the Environment Agency was in itself a step towards this goal, as it brought many facets of environmental management which had previously been separated, (such as waste licensing and integrated pollution control), under the same authority as 'traditional river management activities' such as fisheries, ecology, water quality and flood defence.

The drive forwards has however recently been accelerated with the specific inclusion of integrated river basin management in the nine central 'Environmental Themes' which form the core of current Environment Agency policy and agenda.

Practical integrated river basin management needs good quality environmental data on which to make informed management decissions and impliment sound and sustainable policies. Fluvial geomorphology has a key role to play in this informing of the integrated river basin management process, in that the collection and interpretation of fluvial geomorphological data are important to many facets of catchment management, not least of which is flood defence.

This research seeks to develop methodologies and collect data that will help contribute to the wider development of geomorphology within integrated river basin management in the Environment Agency. As a starting point some more fundimental definitions are perhaps required, such as 'what is fluvial geomorphology' and 'what is flood defence'? Additionally, a more detailed account of the role of geomorphological issues within flood defence and the Environment Agency will also be given.

1.2 What is Fluvial Geomorphology?

Fluvial geomorphology means literally 'land-forms from rivers'. It has been defined as: "the study and analysis of; the process of sediment-transfer (i.e. erosion/entrainment, transport and deposition) in river channels, and of the channel forms and impacts produced by these processes", (Brookes, 1994).

These phases of sediment-transfer form the basis of geomorphological processes. They may be considered individually as different components in the 'sediment life-cycle' which starts with the *erosion* of sediment either directly from the margins of a watercourse, or indirectly from the wider land surface of a catchment which is then carried to a watercourse by the runoff of rainfall, (Clowes and Comfort, 1982). Once in a watercourse sediments are transported downstream, travelling in different ways. Coarser particles act as *bedload* sliding and rolling along the riverbed; bedload also includes the transport of particles which are bouncing and saltating along the bed. Finer particles which are carried in the water column without regular contact with the bed are termed *suspended load*, whilst dissolved minerals are also transported within the water column as the *solute load*, (White, Mottershed and Harrison, 1984). This view of geomorphological processes is massively simplified, in fact this field is viewed by many to be one of the most complex of the earth sciences, (Newson, 1992, for example compares it thus with hydrology, 'runoff prediction can prove relatively easy, sediment-transfer is much more difficult'). That said, a wealth of research has been undertaken on each of these phases of sediment-transfer, and this will be discussed in more detail in the section 'geomorphological science' amongst others below.

1.3 What is Flood Defence?

Flooding, both fluvial flooding from rivers and coastal flooding from the sea, is a natural event which has the potential to devastate property, threaten livelihoods and even take lives. The aim of flood defence is to protect people, their homes and their workplaces from flooding wherever possible. Responsibility for flood defence is shared between the Environment Agency which covers the larger 'main river' watercourses, and local authorities which have the responsibility as concerns all other watercourse. In

Northwest England alone more than £30 million will be spent over the next three years by the Environment Agency in efforts to improve the flood defences of urban areas, (Environment Agency, 1999a).

Typical methods of preventing fluvial flooding include the construction of walls or embankments, the designation or creation of flood water storage reservoirs, the accurate identification of floodplain extents and the prevention of further development within those floodplain areas, and the maintenance of river channels. Maintenance is undertaken to encourage river channels to retain maximum capacity and conveyance as regards spate flows. Methods of maintenance encompass the management of trees, bushes, grasses and aquatic vegetation, (to reduce friction coefficients at the channel boundary which slow the passage of flows), the maintenance of river banks and structures (bridges, weirs, etc.), and the dredging / removal of sediments from river channels, (which reduce in-channel capacity directly), (Darby and Thorne, 1990). Of these activities, Sear, Newson and Brookes (1995) estimated that sediment-related maintenance alone was likely to cost in excess of £20 million per year across the U.K.

1.4 What are the Geomorphological Issues in the Environment Agency and Flood Defence?

Geomorphology offers a means by which to study and quantify the physical affects of a river system upon the environment and landscape through which it runs; and as such it can be utilised by environmental managers in different ways. In the Environment Agency there are two principal areas of geomorphological application:

Applications for Conservation and Ecology

- Understanding the factors contributing to the stability of natural river channels.
- Predicting adjustments in modified river channels and relating these to the recovery of biological populations.
- Developing alternative designs and strategies, which will work with nature rather than against it.
- Identifying the extent of physical diversity within the banks and bed of a river system, which is an important element in environmental diversity.
- Providing process information for the sympathetic and sustainable design of the

rehabilitation/restoration schemes.

(Adapted from Brookes, 1996).

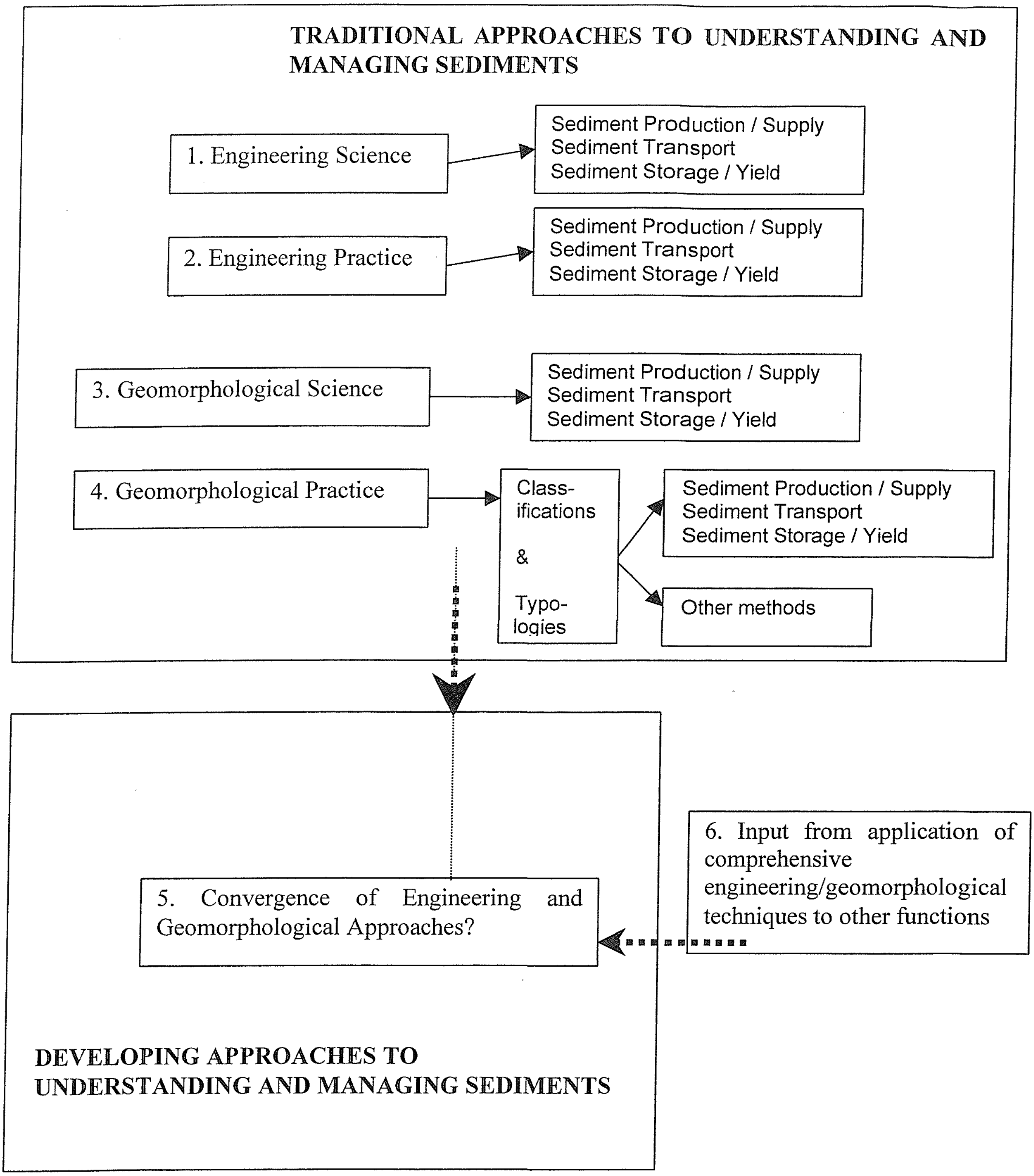
River Engineering Applications:

- The prediction of catchment sediment-yields.
- Impact studies on the morphological and sedimentological effects of river management, e.g. river regulation and flood protection.
- Analysis of the development and change of both plan and section channel morphology, both naturally, and in accordance with management actions.
- Process studies of bank erosion, scour, bedforms, shoal and bar development.
- Studies of contributory factors in flood development, such as landuse change.

(Adapted from Sear and Newson, 1994).

Of these two 'sets' of application, the latter are of principal application to flood defence. Such applications are of particular significance to flood defence maintenance, (which is a costly sphere of operation as shown above). Indeed it will be illustrated below (Section 1.13) that geomorphology is currently making substantial contributions to flood defence; however the two fields have not always meshed together, and traditional approachs to sediment management, and the development of geomorphology, will first be discussed.

Figure 1-1: Summary of the Methods of Understanding and Managing Sediments



1.5 Background to the Management of Sediment Issues

Traditionally sediment science, and the management of sediment issues, have been viewed in two main ways. Firstly, they have been considered at the scale of the single site, through a classical *engineering* approach. Engineers have sought to tackle issues in the form 'problem = erosion or accumulation of sediments at point x, therefore solution = revetment or dredging at point x (and possibly associated points y and z)'. This form of approach has been developed by river and drainage engineers world wide for many years, and the extensive devlopment of technical literature in this field reflects this. A classic example are the U.S. Government technical guidelines such as Keown (1977), though many others also exist, as demonstated below. These have stemmed from the development of a range of formulae from engineering science, aimed at isolating individual sediment processes and calculating them exactly, often based on extensive laboratory study.

Secondly, sediments have been considered within the context of the whole catchment system, with all the stages of 'the sediment life cycle' being acknowledged and studied. This approach has historically tended to be more the preserve of the geomorphologist than engineer. Geomorphological science has tended to separate the processes of erosion, sediment transport and sediment-yield to study them in detail, in the field. However, geomorphological practice has sought to look at these processes collectively. This approach has led to the development of a range of methods for classifying sediment activity in rivers and/or developing catchment models. A typical example of such work is the definition of upland zones of sediment supply, mid-catchment zones of sediment-transfer and lowland zones of sediment storage, (Schumm 1991). Many more will be given below.

Both the engineering and geomorphological approaches to sediment science and practice have made significant advances in the field, but they also have specific shortcomings. These developments and problems are discussed in detail below. However, the crux of the problems experienced by both paradigms may be defined in a single word: *simplification*. Herein lies perhaps the single most frustrating and interesting fact about this whole field of research and practice: sediment-transfer in even the smallest natural catchments expressed completely is intensly complicated, so complex are the processes which govern transfer and the interactions between those processes. This means that simplification is essential in order to express such complexities, but paradoxically over-simplification is often the stumbling block to successful application.

Figure 1.1 above shows a summary of the methods of understanding and managing sediments developed to date, illustrating the different roles that geomorphology and engineering have taken in science and practice. It also illustates the exciting developing approach that has in recent years seen the two disciplines converging and inter-relating. These different roles and developments are discussed in detail below.

1.6 Engineering Science

1.6.1 Erosion:

As with all sediment processes, a series of attempts have been made to express and calculate erosion in terms of formulae. In the floodplain, environmental soil loss and sediment transport to river channels has been extensively examined and the influence of slope and landuse in particular have received attention. The most comprehensive suite of formulae developed for this form of application is the 'universal soil loss equation' (US. Agricultural Research Service, 1961). Formulae have also been developed to express in channel erosion, (Laursen 1952, Apmann 1972 and Agostini et al., 1985). While specialist formulae have been presented to express erosion in specific circumstances such as downstream of spillways, Johnson (1950) and immediately below weirs (D'Agostino, 1994). Computation modelling packages such as the Danish Hydraulic Institutes (DHI) 'MIKE SHE' and 'MIKE BASIN' packages have also incorporated such formulae based approaches into wider catchment modelling utilities, (DHI, 1999).

1.6.2 Transport and yield:

Efforts to isolate and study sediment transport from an engineering perspective have concentrated largely on empirical methods, but such methods have been applied in a broad sense encompassing laboratory synthesis, theoretical derivation and modelling (the development of specialist computer applications). The iterative application of sediment transport formulae to the changing downstream geometry of river systems has also been used to calculate net sediment transport and thus infer yield, particularly in cases of sediment transport modelling, (Halcrow / HR Wallingford 1999).

Laboratory and theoretical work has concentrated upon the production of formulae to describe the processes of sediment-transfer. The expression 'formulae' encompasses a wide variety of techniques. "Formulae are founded upon the premise that a specific relation exists between hydraulic variables (e.g. flow velocity, flow depth, energy gradient and discharge), sedimentological parameters (eg. grain size), and the rate at which bedload [sediment] is transported", (Gomez and Church, 1989, p. 1161). Such tools have been frequently presented as mathematical equations, but graphical analysis techniques, such as 'transport curves', have also been presented. The evolution of formulae development extends back over the past one hundred and twenty one years to Duboys, (1879) attempts to predict gravel movement in the Seine. Subsequent years have seen a wealth of techniques devised in efforts to describe sediment transport. The iterative application of such methods, to changing downstream river channel geometry, may be used to calculate net sediment-yield.

The development of such formulae is typically a two-stage process. In the first stage a relation between bedload transport and hydraulic/sedimentological parameters is described and an initial equation produced, this relation can be developed in one of three ways. Most frequently, it is developed by describing the transport conditions in a suite of experimental data, typically derived from flume experiments, including; DuBoys (1879), Gilbert (1914), Schoklitsch (1934), Shields (1936), Meyer-Peter and Muller (1948), Einstein (1950), Laursen (1958), Colby (1964), Engelund and Hansen (1967), Whitehouse and Hartisty (1988), Warburton and Davies (1994). Secondly, and rarely, a relationship can be developed by describing the transport conditions in a suite of experimental and field data, e.g. Colby (1964) and Toffaletti (1969), or solely a suite of field data, e.g. Carling (1983), Parker (1990), and Laronne, *et al.* (1995). Thirdly, a relationship can be developed from basic physical or mechanical principles, e.g. Yalin (1963), Bagnold (1966),Yang (1972), Ackers and White (1973), Bridge (1981), Hurley (1992). In the second stage, the initial equation is often modified in the light of its performance against data other than those for which it was initially calculated, arising from previous or subsequent research by the author, or by others working in the field, e.g. Meyers-Peter, Favre and Einstein (1934), and Brown (1950). Or in the case of formulae produced by theoretical derivation, modified by calibration to a range of available data, e.g. Einstein's original bedload formula (1950), Laursen (1958), and Ackers and White (1973). In all cases this modification represents an attempt to adapt the formula to wider or universal application.

Recent decades have seen the development of a second approach to the 'empirical' assessment of sediment-transfer. A number of specialised engineering applications have been produced in an attempt to model sediment transport. By automating the process of applying transport equations longitudinally through a river system, they also produce estimates of net yield. Industry-standard applications take the form of 'bolt-on' sediment-transfer modules for the major hydrodynamic and steady-state flow estimation models, such as ISIS, MIKE11 and HEC2/RAS. The latter (HEC-6), designed by the Hydrologic Engineering Centre (1977), has been used in an international context, and particularly in the U.S.A., (Hall, Thomas and Pearson, 1992 and Wang and Han, 1994), while ISIS Sediment has been applied to gravel bed rivers in a U.K. context, (Walker, 2000a). Such applications incorporate a range of empirical formulae along with hydrologic and hydraulic information necessary for flood modelling, and produce estimates of sediment-transfer rates and changing bed levels, temporally at desired locations. Relatively few studies have been conducted to assess the applicability of such models, (Tingsanchali and Sulpharatid, 1996). However, results have been obtained when the output of models have been compared to field data from systems similar to those in which the models were originally developed, e.g. large lowland rivers, (Williams, 1977; Gee, 1984). Feasible results have also been obtained when modelling long-term sediment-yields in large fine-gravel bed rivers, (Havis et al., 1996).

1.7 Shortcomings of Engineering Science Approach

There are also a number of problems associated with empirically based approaches. Typically formulae are developed using a relatively limited range of observations, obtained from the findings of one, or a small group of researchers. "Most formulae thus owe their derivation to a comparatively restricted database, while their utility has been established on the basis of relatively few, (if any), field datasets", (Gomez and Church, 1989, p.1161).

Secondly, the flume experiment, which has formed the primary tool for producing formulae throughout the history of their development, has a number of drawbacks. It is difficult for any scale model to reflect faithfully the many factors of variation that combine to affect bedload transport such as; local hydraulic variation, variations in channel geometry and plan morphology, and changes in bed composition sediment size, texture, shape, and size distribution. Additionally, the flume environment has a tendency to impose factors upon experimental results that are rarely observed in natural systems. For example, experimental findings often relate solely to 'steady flow and equilibrium transport conditions', and specific problems, such as side-wall effects, can further affect findings.

Finally, at a practical level of application, few of the datasets used to develop many sediment transport formulae, whether of field or laboratory origin, relate to sediment sizes larger than sand/fine gravel, and most have little consideration for sorted and armoured bed structures, whereas many river systems exhibit coarser beds with some degree of structural organisation, (Bathurst, Graf and Cao, 1987; Sear 1996).

Modelling sediment-transfer also has its drawbacks. Most of the major commercial models are one-dimensional and therefore have no provision to simulate the effects of meanders or lateral changes in bed-slope. Additionally, as they rely for their core analysis upon existing empirical formulae, (e.g. Engelund and Hansen, Ackers and White in the cases of ISIS and MIKE11, and Duboys, Meyer-Peter and Muller amongst others, in the case of HEC-6), the same root criticisms that are raised above apply concerning their application. However they can be used to model longer-term catchment-scale sediment issues, and can locate 'sediment flux divergences' i.e.

transitions between greater - lesser or lesser - greater sediment transport capacity, (Walker, 2000a). This form of basic modelling analysis can be used to identify potential hot-spots of erosion and deposition that can cause potential maintenance problems for Flood Defence, as illustrated in the work undertaken by Sear et al. (1994) on the Mimmshall Brook.

1.8 Engineering Practice

Despite the wide-ranging research into engineering aspects of sediment-transfer processes, the practices of river management and maintenance have, until recently, been less diverse. Technical manuals addressing the subject were produced in Europe and the US as early as the 1920s and 1930s, (Curd 1921, Drisko 1933); and by the late 1960s / early 1970s a wealth of technical literature was available detailing river engineering works around the world, (Carey 1966, Nixon 1966, Asheson 1968, Hankundy 1971, Sikka 1973).

Traditionally the management of river works in the U.K. was the preserve of the engineer, and geomorphological processes were largely only considered in terms of problems for river maintenance (largely bank erosion and channel deposition), and such issues were addressed with engineering solutions. In other words rivers were viewed as a series of problem sites often without any reference to, or indeed knowledge of, conditions upstream or downstream. Common solutions to identified problems were almost entirely 'hard engineering solutions', applied at 'problem sites' with little consideration given to the wider behaviour of a river system in either a spatial or temporal context. River maintenance was undertaken by the National Rivers Authority (NRA) (and its predecessors), the Internal Drainage Boards and the Local Councils, (Sear, Newson and Brookes 1995). In all these organisations engineering departments were largely autonomous, and although some input to maintenance decisions may have come from ecological advisors (particularly in the NRA), none of these bodies retained permanent geomorphological expertise.

1.8.1 Erosion:

An example which typifies this traditional engineering management approach in the context of erosion is the text, *an evaluation of streambank protection methods*, (Keown, 1977), in which the most widely used methods of addressing erosion during the 1970's are described, along with guidance notes for their application. The principal methods suggested are; stone riprap, concrete pavement, articulated concrete mattresses, transverse dikes, fences, asphalt mix, jacks, gabions, synthetic matting and bulkheads. The only 'soft engineering option' is vegetation, in this context described as a 'short uniform sward of grass'. Additional methods included; ceramics, rubble, concrete or cellular blocks, used-tire matting and automobile bodies. Under 'new methods' such novel materials as 'local waste products', and 'military surplus products' were also suggested. Interestingly a number of methods are also described which had been used in the late 1800's and the early part of this century, such as willow-bundles, timber-and-brush mattresses, and log cribs (deflectors). Considered obsolete in the 1970's, traditional practices using local material would later enjoy something of a renaissance.

1.8.2 Transport and yield:

Likewise problems of sediment transport and deposition would be considered as isolated river sites where the channel geometry or hydraulic conditions were conducive to the accumulation of sediments. Such problems were managed by removing (dredging) sediments from the problem areas, (Darby and Thorne, 1990). If any attempts were made to examine the reasons were the deposition, then usually they would involve little more than a site-based study. The key working methods to address such problems was the assessment of rates of settlement by the selection and application of appropriate sediment transport equations. ‘Solutions’ would then be implemented that altered the geometry and/or hydraulic condition of the channel to a form more conducive to the conveyance of sediments, (such as the installation of deflectors or low flow channels). The potential of such actions simply to transfer the effects of a problem downstream were rarely addressed. The text *Sedimentation Engineering,* (Vanoni 1975), gives many examples of this form of working approach.

Specific sediment deposition problems, such as accumulation in reservoirs, triggered the development of site-based management techniques such as trapping and flushing, and the use of 'dead storage' in reservoir volume calculations, (i.e. writing off a proportion of the reservoir capacity to sediment accumulation). Lopes and Meyer (1993) give a comprehensive review of such traditional techniques.

1.9 Shortcomings with Traditional Engineering Practice

Such traditional engineering practices left a legacy of maintained river channels, which bear little resemblance to natural riverine environments. Historically such engineered riverine environments were accepted as a management necessity. However, by the 1980's increasing demand for environmental sensitivity in all walks of environmental management began to affect this view. Although the real catalyst for change was perhaps not so much the ground-swell of changing environmental opinion in the U.K., but the realisation that many hard engineering solutions were simply not delivering. Many schemes were not fulfilling their design life expectancy, others were producing costly ongoing maintenance requirements, or were simply transferring problems elsewhere in river systems. Such observations in the UK and Europe, (Ritter 1979, Keller and Brookes 1984, Schumm et al. 1984). were supported by research findings elsewhere, such as those in the US, (Parker and Andres 1976, Dunne and Leopold 1978).

Such realisations brought about certain changes in the ethos of engineering practice in the UK. Design and management guidance has increasingly sought to include a greater understanding of the sediment processes at work at the land / water interface that is a river system. Consequently many design manuals now include a much more scientific and comprehensive approach to the derivation of management actions, (e.g. Hemphill and Bramley, (1989), Hey and Heritage, 1993). Texts are also much more geared towards the use of environmentally-friendly methods and materials, softer and more natural materials were preferentially prescribed for use in river works, with hard engineering solutions ranked for 'potential to soften', and reserved for severe situations. Examples of developments in 'soft engineering solutions' to bank erosion, for instance, included the consideration of many different forms of vegetative cover, such as a reassessment of the benefits of traditional materials, e.g. willow, osier and ash. In addition, a whole new suite of artificial materials, the 'geotextiles' were developed to synthesise or assist natural vegetative colonisation. (Environment Agency, 1999b).

However, the underlying assumptions of such approaches still often view sediment-transfer issues as site-specific problems, without considering the wider implications both of the symptoms and of any solutions proposed. There is evidence that a move to considering sediment-transfer issues in a catchment-wide context is occurring in some areas of engineering practice; however such changes are occurring at the intersect between the geomorphological and engineering paradigms, and as such they will be discussed in more detail in Section 1.13 below.

1.10 Geomorphological Science

1.10.1 Erosion:

Historically the nature and impacts of fluvial erosion, both within the river channel environment and on the floodplain, have been the subject of much research. Lawler (1993), comprehensively reviewed bank erosion and channel change research, citing numerous studies including early works, which emphasize the rapidity of erosion (Wolman 1959; Schumm and Lichty 1963), and later contributions that emphasise the complexity of the processes governing it, (Hooke 1979; Knighton 1973; Lawler 1987). The physical interactions between erosion, channel change and the floodplain have also been examined, (Lewin 1972 and Mosley 1975), as has the role of geology, (Fisk, 1952). Research has also addressed the importance of bank erosion in the ecological development of the river environment and its floodplain, (Nanson and Beach, 1977). More recently studies have concentrated on the development of innovative ways of assessing bank erosion rates, such as the development of 'photo-electric erosion pins' (PEEPs), Lawler, Harris and Leeks, (1997).

1.10.2 Sediment transport:

The transport of sediment particles has been a frequent focus of research activity. The study of the movement of coarse sediment particles (gravels and cobbles) in natural river systems has been identified as commencing in the early 1960's, (Hassan and Church, 1992). Such work centres on the identification of individual riverbed clasts, and the tracking of their movement over time. A great range of tracer techniques has been employed to observe particle transport. This includes clasts that are: painted, (Slaymaker, 1972; Ashworth, 1987; Komar and Carling, 1991), Luminophor covered, (Weiss, 1994), tagged, (Butler, 1977), magnetically imbedded, (Hassan and Church, 1992; Gintz, Hassan and Schmidt, 1996), and radioactively labelled, (Stelczer, 1981); in addition clasts have been fitted with radio transmitters, (Schmidt and Ergenzinger, 1992; Busskamp, 1994), and clasts selected that are lithologically discrete from natural bedload, (Mosley, 1978; Kondolf and Matthews, 1986). Further recent examples are provided by Sear et al. (2000).

The transport of finer-grained sediments (sands and silts) is more difficult to observe directly in the field, though it may be easier to monitor. Depending on the energy characteristics of a river channel, such material may be transported as bedload, or may be primarily transported as suspended load, travelling in suspension within the water column, and having little contact with the riverbed. Transport of such particles is measured by either pump sampling or bottle sampling, (methods of the latter may be sub-divided into 'standard, depth-integrated and Delft bottle techniques), (Lawrence, 1996). There are many examples of the application of such techniques from around the world, (e.g. Crickmore and Aked ,1975; Fish, 1983; Bosman et al., 1987; Mohanty, 1988).

Standard bottle samples simply remove a set volume from the water column and the suspended sediments contained in that sample are then removed. This is done either on-site or subsequently in a laboratory by filtration and/or evaporation, or alternatively the whole sample is analysed in suspension using some form of laser particle analysis tool, such as a Coulter-counter. The depth-integrated bottle sampler expands a little on this method as it is designed to be raised and lowered within the water column to standardise the collection of suspended material, (Nelson and Benedict, 1951). Delft bottles draw water from the river up a pipe through a settlement bottle and back to the river, samples are thus large, and suspended sediments isolated immediately. Pump sampling uses a pump to suck water through a fine sieve, again sampling large volumes. Such methods were pioneered by the U.S. National Parks Service, (NPS, 1983).

The findings of such fine sediment transport investigations have most frequently been used to develop relationships between discharge variation and fine sediment concentration, (Walling and Webb 1982 and Carling 1983). However, considerable interest has also been shown in quantifying fine sediment transport for fisheries impacts, (Carling and Reader, 1989, and Orr and Quinn, 1998), and water quality, indeed it is part of the core Environment Agency duties to collect data in this field.

1.10.3 Sediment-yield:

There have been many techniques utilised to observe sediment-yield in the field, and examples of such methods follow. Direct observations of bedload transfer during flood events have been made, (e.g. Campbell and Sidle, 1985; Adenlof and Wohl, 1994), using mobile samplers, of which the most commonly utilised is the 'Helly-Smith bedload sampler'. Pits and traps have been installed in riverbeds from the arctic to the tropics, and the deposition of sediment in such devices monitored over time with changes in flow. Examples of this work include Moore and Newson (1986), Bezinge *et al.* (1989), Billi (1993), Becht (1994), Barsh *et al.* (1994). Timescales for these studies vary from a few days to several years. Automated traps have also been developed, particularly for use in monitoring bedload transfer during arid-zone flash floods, which incorporate pressure transducers to quantify changing yield during a single spate flow event, Laronne and Reid (1993) and Reid *et al.* (1995). Changes in bedload flux within a given reach of a river channel have been monitored by repeated topographical surveys, (Schmidt, 1994; Goff and Ashmore, 1994; Martin and Church, 1995). Higher-tech devices such as magnetic and acoustic detectors have also been used to quantify sediment-yield under spate conditions, (Ergenzinger and Custer, 1983; Bunte, 1992; Rickenmann, 1994).

The observation of sediment accumulation in natural and artificial waterbodies gives a method for assessing total sediment-yield, as such areas of open standing water typically serve to provide a settling environment, in which both bedload and suspended load is deposited. Such sediment storage characteristics of reservoirs have been used to quantify yield by researchers such as Butcher et al. (1992), Duck and McManus (1994) and Walker (1995).

1.11 Shortcomings of the Geomorphological Science Approach

The techniques for obtaining field observations of sediment-transfer discussed above, are not without their drawbacks. Transfer is one of the most difficult fluvial parameters to measure accurately in the field, as major transfer events are frequently associated with relatively large, infrequent discharge events.

The nature of the transfer process also creates problems, i.e. the bed of the study site, which forms a convenient platform from which to observe most other in-channel processes, is mobile. This tends to mean that direct measurements of sediment-transfer as it occurs, e.g. by Helly-Smith sampler, can be inaccurate, (Gaudet, Roy and Best, 1994).

Indirect methods of sampling, such as tracing the transport of individual clasts, collecting a portion of the transmitted sediment-yield in some form of trap, or sampling fine sediments using pump or bottle-sampling, examine only a proportion of the sediments in transit, and are therefore prone to general and specific inaccuracies. General inaccuracies stem from the statistical relationship between the small size of the sample, and the overall mass of sediment-transferred. For instance if one wishes to characterise the average particle size of sediments by trapping, Church et al. (1987) have shown that, in the case of coarser sediments, many tonnes of sediment may be required to get a sample statistically representative of the wider bed.

In the case of specific inaccuracies, those concerning tracers include burial and low retrieval rates, (Weiss, 1994). Such problems have been addressed to some degree by recent developments in the field such as the refinement of magnetic and electronic tracing techniques, Sear et al. (2000). In the case of pit traps, individual step lengths of particles may also exceed the width of a trap or traps that overfill during the course of an event, (Reid, Frostick and Layman, 1985). In the case of bottle/pump sampling, stratification of sediments in transit within the water-column, for example as a result of temperature effects, may mean that the sample is non-representative. Other specific effects include the placement of field equipment within a channel, which can greatly affect observed data. For example, traps located in/adjacent to different bed features may receive different inputs of bedload over the same event, (Sear, 1996), and the placement of erosion pins into a river bank may disturb that bank making it more prone to erosion and effecting the rates recorded, (Lawler, 1993).

Comprehensive field datasets are very time-consuming to compile. It may take several years of observations before a representative example of flows and transport conditions is developed, (Moore and Newson, 1986; Martin and Church, 1995). Even then a dataset may not contain examples of sediment-transfer during extreme flow conditions, which occur rarely, but nevertheless can account for a large proportion of a long-term sediment-transfer budget.

Perhaps the most significant drawback to findings from the field is that ultimately any dataset, no matter how complete and extensive, is directly applicable to the calculation and estimation of sediment-transfer at the site of observation only. Data may give an indication of likely transfer behaviour elsewhere in a system, or even at sites with similar characteristics on rivers elsewhere, but the subjectivity of individual site variables means that such indications will at best only be approximately correct.

1.12 Geomorphological Practice

In addition to the scientific consideration and study of individual geomorphological processes in the field, the wider consideration of individual rivers, river systems and catchments over the past 100 years or more has developed a large number of practical theories. Such theories frequently relate to the way that geomorphological process and form vary spatially and temporally in river systems, and as such they have often led to the development of 'classifications' or 'typologies'. The desire to categorise elements within a paradigm or study area is not new, indeed classifications and typologies, as expressed in such schemes as botanical taxonomies or chemical tables of elements, underpin the essence of modern science.

The terms classification and typology have historically been used somewhat inter-changeably, however it is perhaps worth making the following distinction by way of definition in the context of geomorphology and sediment-transfer. Classifications of catchments, river systems, rivers and / or tributaries or river reaches (constituent river sections) may be said to assign classes based on similar physical characteristics, features or forms. Typologies meanwhile assign types based on the occurrence of similar physical processes, (e.g. sediment-transfer activity, or lack of activity). Both classifications and typologies may be based upon the consideration of different erosion, transport and deposition classes or variations on this terminology. However many other types of riverine class divisions exist based both on form and on processes. Examples of classifications and typologies previously devised will be examined below. During the last decade there has also been a development of methods that are specifically applicable to issues of river management. These are methods by which classifications and typologies may be developed using a wide range of form and process information often necessitating detailed data collection methods. These *'data collection practices'* will be discussed separately below.

1.12.1 Classifications and typologies:

Within the earth and environmental sciences, classifications have been developed to divide watercourses into categories for many different issues, such as variations in water quality, fisheries and biological diversity (Environment Agency, 1995; Environment Agency, 1996 and Carle and Strub, 1978). However, such classifications are outside the remit of this review, which will concentrate solely on geomorphological and related classifications.

The concept of a catchment classification in geomorphology is not new. Mosley (1987) in his review 'The classification and characterisation of rivers' cites Powell (1875) as an early example, which sought to develop a typology, based on the underlying geology of rivers.

Rosgen (1996) cites a series of examples of classifications using sediment-transfer factors, commencing with the work of Davis (1899) who divided streams into classes based on their relative energy, comparing them to the human lifecycle as 'youthful, mature and old age' systems. 'Youthful' equated to systems actively eroding new sediments at present, 'mature' implied that erosion and deposition were moderate and balanced (thus implying that transport predominates), and 'old age' classified depositional environments. Brookes and Sear (1996) provide an example of this basic type of '3-stage' approach to catchment classification, (as illustrated in Figure 1.2), showing the split between upland (zone of sediment supply), middle orders (zone of sediment transport) and lowland (zone of sediment storage) channel types, and the changing stream energy and substrate sizes in these different environments.

Nevins (1965) has also produced classifications that divide reaches on the basis of changes in geology along the longitudinal profile of a channel. Leopold and Wolman (1957) and Popov (1964), amongst others have produced classifications, which divide rivers on the basis of variations in plan-form morphology, such as straight through meandering to braided river systems. Thornbury (1969) developed a system based on valley types.

Brice (1984) and Schumm (1963) developed typologies (considering geomorphological processes) based on channel activity, such as the development of a sliding scale of channel characteristics that encompasses eroding, stable and depositing environments. Schumm (1977) expanded on this activity principle to include sediment transport and channel dimensions into a classification system. Selby (1985) again expanded on this work to include a consideration of sediment size characteristics. More recently, Downs and Gregory (1993) examined the role of channel activity in the sensitivity of rivers to man-made catchment changes. Padmore, Newson and Charlton (1997) have determined forms of channel characterisation based on physical biotopes.

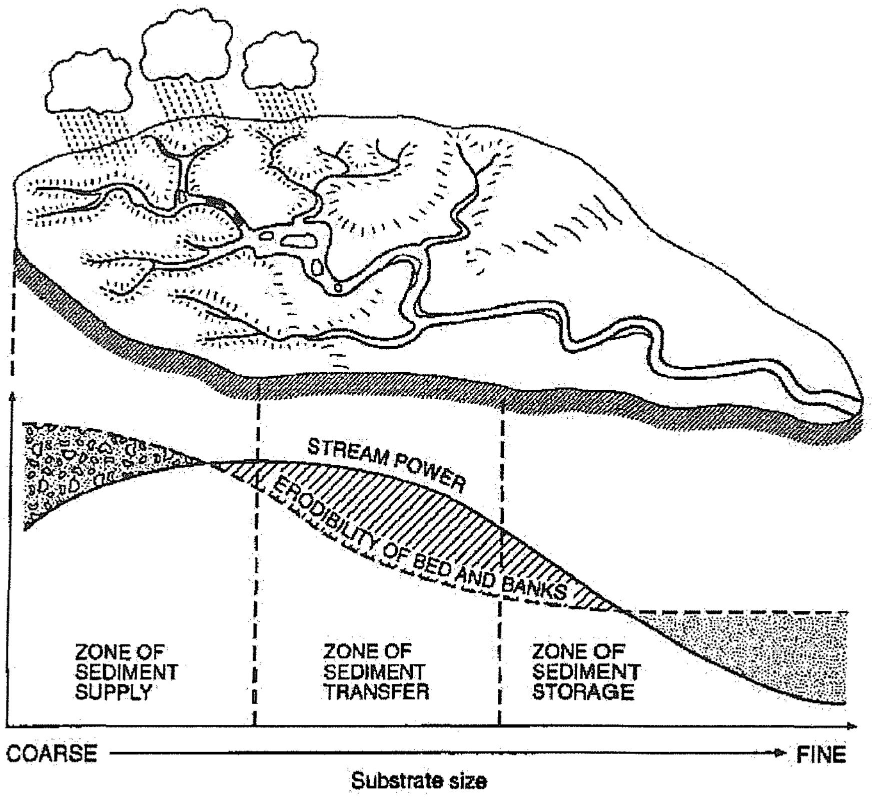


Figure 1-2: A Simple Approach to Catchment Classification

(After Brookes and Sear, 1996 p.87).

Multi-variate analysis techniques have been used to introduce objectivity into the assignment of a channel to different reach classifications. Wood-Smith and Buffington (1996) for example, related geomorphological variables to the impacts of landuse change. Computerised methods such as the TWINSPAN package have also been employed for objective reach derivation, particularly as concerns the well documented relationships between morphological variation and the composition of a macro-invertebrate community, (Furse et al. 1984).

Technological advances in the fields of satellite imagery and Geographical Information Systems (GIS) have also provided new tools with which to assess and classify catchments, and new methods of analysing and displaying such classifications: for example the planform category work of Noorbergen (1993), and the classification of channel reaches by lateral erosion activity of Downward (1995).

The extensive dataset of the River Habitat Survey (RHS) collected between 1994 and 1996, and comprising a randomly-distributed, statistically-representative sample of the river network of the U.K., has also been used to produce a number of classifications of river types. Most significant among these, in terms of their extent and application, have been the indices of 'Habitat Modification' and 'Habitat Quality'. The former quantifies the degree of engineering alteration and management undertaken at a river site (i.e. the degree to which a site has been modified from its 'natural' state). The latter assesses the occurrence of rare features, such as riverside wetland, ancient woodland, waterfalls, etc. (i.e. the degree to which a site is rare, and therefore of high quality, in a national context), (Environment Agency, 1997).

The Rosgen (1996) system for the classification of natural rivers uses a number of indicators of geomorphological form, namely sinuosity, slope, entrenchment, width / depth ratio and substrate type to divide rivers into 8 primary and 92 secondary categories. The method was developed in the U.S. using an expert systems approach to the selection of indicators and a dataset of river sites collected over many years representing a wide, though not necessarily randomly-distributed, coverage of environments. This work has seen worldwide distribution, and has met with critical acclaim, (that will be discussed in more detail in the short-comings section below).

1.12.2 Data collection practices:

The Catchment Baseline Survey (CBS) methodology developed jointly by the Universities of Nottingham, Newcastle and Southampton (1997), collects basic information on geomorphological form such as valley form, planform, gradient, geometry, substrate and bank materials and evidence of maintenance and management. It is designed as a relatively quick, low-cost survey methodology enabling the collection of baseline geomorphological data. It has been used to classify rivers into reach types for a range of management applications, including Flood Defence maintenance issues, (examples are given in Section 1.13). Shortcomings of this methodology, as concerns flood defence maintenance application are discussed below.

The Fluvial Audit (FA) methodology, also developed jointly by the Universities of Nottingham, Newcastle and Southampton (1997), expands upon the basic information collected in the Catchment Baseline Survey. It includes greater detail on valley-form and channel geometry as well as information on bedforms and a relatively detailed break down of types of sediment sources and sinks. It also constitutes a detailed investigation of the management / maintenance history of a reach, or more usually, river catchment, and an examination of the operation of geomorphological processes over the longer term using archive data such as historic maps. It has also been used to classify rivers into reaches for management applications. Again examples of such applications are given below in Section 1.13 and shortcomings of the approach are discussed below.

The two methods above (CBS and FA) form two 'levels' of river / catchment classification and assessment. These methods may then be augmented by the completion of a Bank Assessment Record Sheet, (the Universities of Nottingham, Newcastle and Southampton 1997), or a Stream Reconnaissance Sheet (Thorne 1998), depending on whether the management application under consideration is one pertaining purely to river bank management (i.e. an erosion problem), or wider considerations. These methods are very detailed and are intended to provide site-specific information to complement the wider considerations of the CBS and FA. As such they are not catchment tools, and they are not used directly in the development of classifications or typologies.

The River Channel Typology (RCT) (Universities of Southampton and Newcastle 1995 and Universities of Southampton and Newcastle 1999) analysed a number of sediment-transfer parameters from the RHS database (outlined above). Such parameters included the presence of 'eroding cliff' and deposition features 'side / point / mid-channel bars', in addition to other geomorphological process indicators such as substrate, bedforms, flow-types and sinuosity. A statistical approach to defining river types was adopted using the TWINSPAN programme to separate river types on the presence / absence and percentage occurrence of these parameters. This approach produced a typology as part of the National Rivers Authority research and development programme, designed to assist in practical issues of river management.

1.13 Shortcomings of Geomorphological Practice

Traditionally river classification typologies and techniques have not been applied holistically to geomorphological processes, rather they are based typically on one or two key variables that are selected subjectively. Such a criticism could apply to the majority of early efforts at river classification, e.g. Powell (1875), Davis (1899), Nevins (1965), Schumm (1963), and many of the other examples given above. This provides an esoteric overview of a catchment, but it does not provide a comprehensive picture of the ranges of geomorphological processes and activity. As is the case with sediment-transfer formulae or site-based geomorphological science observations discussed in the sections above, the accuracy of the application of classifications is largely limited to the catchments on which they were developed.

Of those catchment classifications that have been developed to describe a range of geomorphological processes, some have not been quantified with observations and measurements in the field, (e.g. Schumm 1963 and 1977; Brice 1984 and Selby 1985). Therefore such techniques typically provide dimensionless indices or scales of change which are difficult to relate to real measurements, such as rates of sediment-yield or bank retreat for instance, which may be required for application to river engineering. There are however techniques which include information on a range of geomorphological forms and/or processes, and which have strong links to field-based observations. These are the classification method of Rosgen (1996), and the data collection methods of RCT (Universities of Southampton and Newcastle 1995 and 1999) based on RHS data, CBS and FA (Universities of Nottingham, Newcastle and Southampton 1997).

The Rosgen method is based on the subjective assessment of a small number of factors of geomorphological form, e.g. sinuosity, gradient, substrate, width / depth and entrenchment. However, such factors can also by inference say a lot about the geomorphological processes operating to produce such forms. This basis for assessment might be viewed as both a strength and a weakness. On the plus side it is practical to undertake in the field and quick to perform. On the negative side it is subjective, and the simplicity of the approach perhaps masks many detailed geomorphological variations that may be of management interest. The major criticisms of Rosgen in the context of this review however, is that his work was developed entirely on U.S. river systems and applies only to natural rivers. Therefore it is debatable whether many of the categories developed are generally applicable outside the U.S., especially in countries which do not have the extremes of climate and altitude variation of the States. Most significantly though is the term 'natural' in Rosgen's classification system, for in terms of river management considerations, such as flood defence and particularly flood defence maintenance, the river systems and the floodplains surrounding them are by their very nature modified, and thus fall outside Rosgen's classification. In fairness, this criticism is perhaps more a criticism of Rosgen's success than of his techniques. It is doubtful that he intended to develop a river classification system for worldwide application. However, the ease of application of the methods described in what is undeniably a very attractive book, containing many fine photographs of wild rivers, has led to perhaps misguided attempts to use it in unsuitable countries / areas, e.g. its use to assess river rehabilitation methods in South West England, (Cooper and Hooke, 1999).

The shortcomings of the RCT approach in terms of its overall appraisal of geomorphological forms and processes and its potential application flood defence management lie in two camps; the intentionally-generic nature of RHS data, and the limitations of TWINSPAN as a statistical tool. RHS is designed to collect physical data on the river environment that encompasses the widest range of environmental management interests, e.g. landscape, ecological, botanical, in addition to basic information on channel engineering / management and geomorphology. Therefore the base geomorphological data available to the RCT was limited and so the resulting classification may miss some finer elements of geomorphological variation. A second, though less severe shortcoming is that the TWINSPAN package used to determine breaks in the classification system is an ecological package developed for identifying discrete plant communities. This approach considers 'species' to be singular, uniquely defined, independently-occurring entities. In the case of the RCT application the 'species' were often a more complicated combination of features of which the predominant one was expressed, (such as predominant substrate), or they were independent variables (e.g. point bars), but they might vary in size from a square metre to hundreds of square metres. Also geomorphological features are rarely independently occurring, deposition in one reach (or community in TWINSPAN terminology), may well be linked to erosion within that reach, but it may equally well be linked to erosion in the reach upstream, or the one upstream of that. Such considerations could not be accounted for in this approach.

The CBS and FA techniques developed by the Universities of Nottingham, Newcastle and Southampton (1997) represent arguably the most advanced attempts to apply geomorphological practices to river management problems. However, it may be said that specific needs of flood defence maintenance application falls between these two methods. The CBS methodology collects general geomorphological data and as such is well-suited to a catchment management overview, (and thus utilisation in the initial phases of Local Environment Agency Plans (LEAPS) and other catchment management processes. However, alone it does not collect sufficient details on types of erosion and deposition to offer an analytical review, capable of classifying a river system. Additionally it does not collect information on artificial causes of erosion / deposition, or enhancements of process rates. Therefore it is not possible to suggest a comprehensive management strategy to reduce erosion / sediment supply. The full FA approach does indeed collect a wealth of information suited to producing management suggestions, however it is time-consuming to complete as the information collected is designed to cover the wider sphere of environmental management issues, and not necessarily focused on flood defence needs. However, it is also worth noting that the method does not explicitly relate causes to its observations of erosion / deposition, which may be a weakness in terms of management application.

A final generic problem with all of the methods above is, 'who undertakes the fieldwork / data gathering required by the various different methods'? Indeed this is a problem that may be extrapolated to much of geomorphological practice. There are few formal qualifications in geomorphology at graduate or taught-post-graduate level, and there is no professional body conferring 'chartered status or equivalent' on geomorphologists. Therefore questions of standardisation, interpretation and subjectivity may be levelled in some cases of geomorphological practice.

1.14 The Convergence of the Engineering and Geomorphological Approaches?

There is now evidence that geomorphological and engineering approaches to the management of sediment issues are converging. Engineers are beginning to consider the role of geomorphological processes in the context of the wider sediment budget of a river system, and hence the upstream and downstream impacts of river work. At the same time, geomorphology is diversifying from its academic roots, appealing to new and wider audiences (Newson and Sear, 1997), and providing greater inputs to engineering schemes, (Sear, Newson and Brookes, 1995), (examples of such collaborations are given in Table 1.1 below).

Indeed there is growing evidence to suggest that environmental practitioners in general, and engineers among them, are now starting to consider the management of geomorphological processes at a catchment scale, as an alternative to site-centred measures. Indeed the evidence of the principles of such 'integrated river-basin management' can be seen with reference to the U.K. for some time, (Fiddes and Clifforde 1990; Gardiner 1990; Downs, Gregory and Brookes 1991). Examples of such projects on the ground have perhaps taken a little longer, e.g. the current 'Sustainable rivers management project', (Environment Agency, 2000a), and the Environment Agency's ongoing national research and design project, *Soil erosion run-off rates and sheep-overgrazing*, Environment Agency (1998).

This new interest in catchment-wide management may have been the product of, or the catalyst for, river management reference texts that have been written by geomorphologists for use by engineers and environmental managers, (Brookes 1985; Hey et al. 1991; Hey and Heritage 1993; Thorne et al. 1994; Thorne, Hey and Newson 1997; Thorne 1998). Recent efforts have also been made to increase geomorphological understanding and expertise within the Environment Agency and other national bodies, (Brookes 1996; Beaver and Walker 1998; Walker and Walker 1998; Walker 1999; Universities of Nottingham, Newcastle and Southampton 1998).

The gathering momentum for the inclusion of geomorphological inputs into other areas of channel engineering, such as river restoration, (Sear, 1994), has perhaps also assisted in increasing the drive to include geomorphological consideration in flood defence projects. The following are a few examples of the numerous cases of such inputs to restoration schemes: the River Alt (Nolan and Gutherie, 1996), the Whittle Brook (Scott, Wilson Kirkpatrick, 1996), the River Cole (Sear, Briggs and Brookes, 1998), the River Rother (Walker and Briggs, 1996) and the Mimmishall Brook (Sear et al. 1994). More extensive compilations can be found in Brookes and Shields (1996) and River Restoration Centre (1999).

As mentioned above, the number of engineering projects that are now including geomorphological contributions in the Environment Agency is increasing rapidly. This is particularly true of flood defence maintenance and Table 1.1 below provides many examples of such schemes. It also gives an indication as to whether such contributions included the use of a site-based catchment-wide geomorphological 'data collection method' (e.g. catchment baseline audit, fluvial audit, etc.).

Table 1-1: Case Studies of Geomorphological Applications to Flood Defence Maintenance Problems

(Adapted and extended from University of Newcastle, 1998).

Location, (Environment Agency Region)	Maintenance Problem	Summary of Geomorphological Recommendations	Catchment wide geomorphological data collection methods used?	Reference Source
Mimmishall Brook, (Thames)	Shoal removal every 2 years	Control erosion in upper catchment and restore meanders locally	Yes, fluvial audit	Sear and Newson (1994)
River Wansbeck (Northeast)	Shoal removal every 5 years	Sediment supply stable, allow shoal development	Yes, (partial) catchment baseline audit	Sear and Newson (1994)
River Ure (Northeast)	One-off erosion scheme at floodbank	Short term repairs, long term set bank embankment	Yes, catchment baseline audit	Sear and Newson (1994)
River Ehen (Northwest)	Bank protection proposed	Long term adjustment to major flood, accept erosion and leave alone	Yes, fluvial audit	Newson and Sear (1992)

Rivers Derwent / Rhye (Northeast)	Local desilting annually	Control bank poaching upstream and encourage soil conservation	Yes, fluvial audit	Sear and Newson (1994)
River Scence (Midlands)	Dredged every 10 years, local desilting annually	Alter channel geometry and control bank poaching upstream	Yes, fluvial audit	Sear and Newson (1994)
River Idle (Midlands)	Proposed dredging of channel	Selective monitoring and implementation of soil conservation strategy	Yes, limited catchment baseline audit	Sear and Newson (1994)
Shelf Brook (Northwest)	Shoaling problems identified	Construct gravel traps	Yes, modified fluvial audit / sediment-transfer appraisal	Sear and Newson (1994)
Tawe (Welsh)	Shoaling problems identified	Monitor to establish if shoaling effects flood capacity	Yes, catchment baseline audit	Sear and Newson (1994)
Lake District Gravel traps (Northwest)	Bedload yields and maintenance conditions unknown	Bedload yields produced, implications for downstream impacts and future maintenance produced	None	Sear and Newson (1994)
River Alma (Northeast)	Sediment accumulation upstream of weir	Increasing flood carrying capacity by raising walls, and potentially clearing sediments with deflectors	Yes, catchment baseline audit	Sear and Newson (1994)
Chalvey Ditch (Thames)	Silt accumulation due to weirs	Weir removal recommended	Yes, fluvial audit	Walker and Sear (1996a)
River Crane (Thames)	Assessment of maintenance requirements post flood defence scheme	Minor repairs to weir and bank protection required	Yes, catchment baseline audit	Walker and Sear (1996b)
Rivers Brent and Crane (Thames)	Lack of catchment knowledge concerning sediment processes	Potential maintenance sites identified (along with potential rehabilitation sites)	None	Briggs, Walker and Sear (1996)
Upper Severn (Midlands)	Overview of maintenance practices, particularly erosion needed	Identification of focus areas for maintenance, guidance on changes to channel geometry suggested	Yes, fluvial audit	Downs, Wood and Thorne (1997)

River Liza (Northwest)	Impact on sediment transport of bridge maintenance	Options for rehabilitating bridge to maintain sediment equilibrium suggested	Yes, fluvial audit	Reed (1995)
River Roch (Northwest)	Impact of sediment transport on flood alleviation design unknown	Quantification of sediment transport, design suggestions to optimise sediment management and minimise maintenance	Yes, adapted fluvial audit	Walker (1997a)
River Keer (Northwest)	Fine sediment accretion	Control bank poaching upstream and encourage soil conservation	Yes, adapted catchment baseline audit	Walker (1997b)
River Brock (Northwest)	Bank erosion threatening footpath	Retreat footpath line	Yes, adapted fluvial audit	Walker (1999)
River Irwell (Northwest)	Shoaling below weir (3 year removal cycle)	Sediment source identified, suggestions to decrease sediment inputs made	None	Birch (1999)
Pendle Water (Northwest)	Bank erosion threatening flood defences	Changes in channel geometry and introduction of bedchecks	None	Walker (1998a)
River Trannon (Midlands)	Bank erosion threatening embankments	Long term erosion rates and key risk areas identified, retreating embankments suggested in these	Yes, fluvial audit	Walker (1997c)

From Table 1.1 it is evident that a growing number of geomorphological contributions to flood defence maintenance applications incorporate site-based catchment-wide geomorphological data gathering processes, often 'rapid appraisal' processes such as catchment baseline audit. However, there are still many questions to be answered concerning the applicability and optimum form of such methods. The remainder of this project focuses on this dynamic aspect of geomorphological application, and the development of a new, robust method of geomorphological auditing. In doing so, attempts will be made to answer a number of key questions concerning the versatllity and utility of such an approach. These questions are developed in the next section as the 'aims and objectives' of this project.

Chaper 2: Statement of Aims and Objectives

2.1 Context

It has been shown above, (in the previous chapter), that geomorphology is a relatively new approach to river management in the U.K., particularly in the work of the Environment Agency and its predecessors. The approach to broad-based catchment assessments, based on the recording of geomorphological and/or other habitat features, has been developed in a number of different ways. i.e. Stream reconnaissance record sheets, (Thorne, 1993), catchment baseline audit, (Universities of Nottingham, Newcastle and Southampton, 1998), River Habitat Survey (Environment Agency, 1997 and Walker, Naura and Diamond, 1998), and a range of variations on the fluvial audit, (e.g. Sear, Darby, Thorne and Brookes 1994; Downs, Wood and Thorne 1997; (Universities of Nottingham, Newcastle and Southampton, 1998). This has been discussed in more detail above in the previous chapter. This range of techniques has however led to variety in the nomenclature describing the methods of geomorphological catchment appraisal. Henceforth, the developing methods presented in this text will be referred to as '*geomorphological audit*', or simply '*audit*' techniques.

There has over the last decade been a number of cases of the application of geomorphological methods to the work of Flood Defence within the Environment Agency. A summary of all cases known to the author is given in Table 1.1 above.

2.2 Aims

Therefore this research aims to answer a number of key questions that relate to the definition of both the content and the role of the geomorphological audit methodology.

It seeks to:

Specify what data need to be collected in an audit, and determine whether these requirements differ for catchments with different management objectives.

Quantify what tangible benefits the audit method can bring to a range of Flood Defence projects at different 'life stages'[1]: e.g. design, feasibility and appraisal.

Assess the role of the audit method in projects of different catchment scales.

Determine what, if any additional geomorphological information needs to be collected or derived, in addition to the observations of the geomorphological audit method, to maximise the geomorphological contribution to example Flood Defence projects.

2.3 Objectives

The objectives of this research are therefore to test a set of key hypotheses:

The first 4 might be summed up in the term 'versatility':

'Is it possible to produce a definitive technique for the collection of geomorphological data that is appropriate to the analysis of forms and processes across a wide range of catchment characteristics'? (In this case *a wide range* may be interpreted to encompass upland and lowland river environments >600 metres and <50 metres above sea-level, a range of bankful stream power values from <30 to >800 w^{-1} m^2, a variety of predominate substrates from large cobbles to fine gravel, a range of non-cohesive bank materials from cobbles to sands, and a wide range of channel / bank vegetation conditions and catchment landuses).

'Can such a definitive technique be considered to be appropriate to application at a range of catchment and sub-catchment scales from a few square kilometres to many hundred'?

1 Flood Defence project 'life-stages' may be defined as the major phases through which a project must progress. These include; inception, feasibility, design, construction and appraisal.

'Is it possible to produce a definitive technique for the collection of geomorphological data that is generally appropriate to different flood defence objectives including, sediment maintenance and sediment trapping'?

'Is it also possible to produce an audit that usefully contributes to the different 'life-stages' of flood defence works, i.e. feasibility, design and post-project appraisal'?

The latter 3 might be summed up by the term 'utility':

'What are the advantages of this audit method over existing methods'?

'What additional data, if any, need to be collected or produced specifically to maximise the contribution of the audit technique to different flood defence objectives'?

'May this definitive technique be applied to produce tangible benefits in the context of flood defence schemes that are significantly greater than the total costs associated with undertaking such techniques'?

2.4 Summary of Techniques Proposed to Achieve Aims and Objectives

The objectives above will be illustrated through two case studies. These two represent the development of a geomorphological audit approach and its application to projects at different 'life-stages', in catchments with different physical characteristics and different flood defence management objectives. These differences are designed to test the *versatility* of the audit approach. The case studies will then be individually and collectively assessed to test the *utility* aspects of the audit.

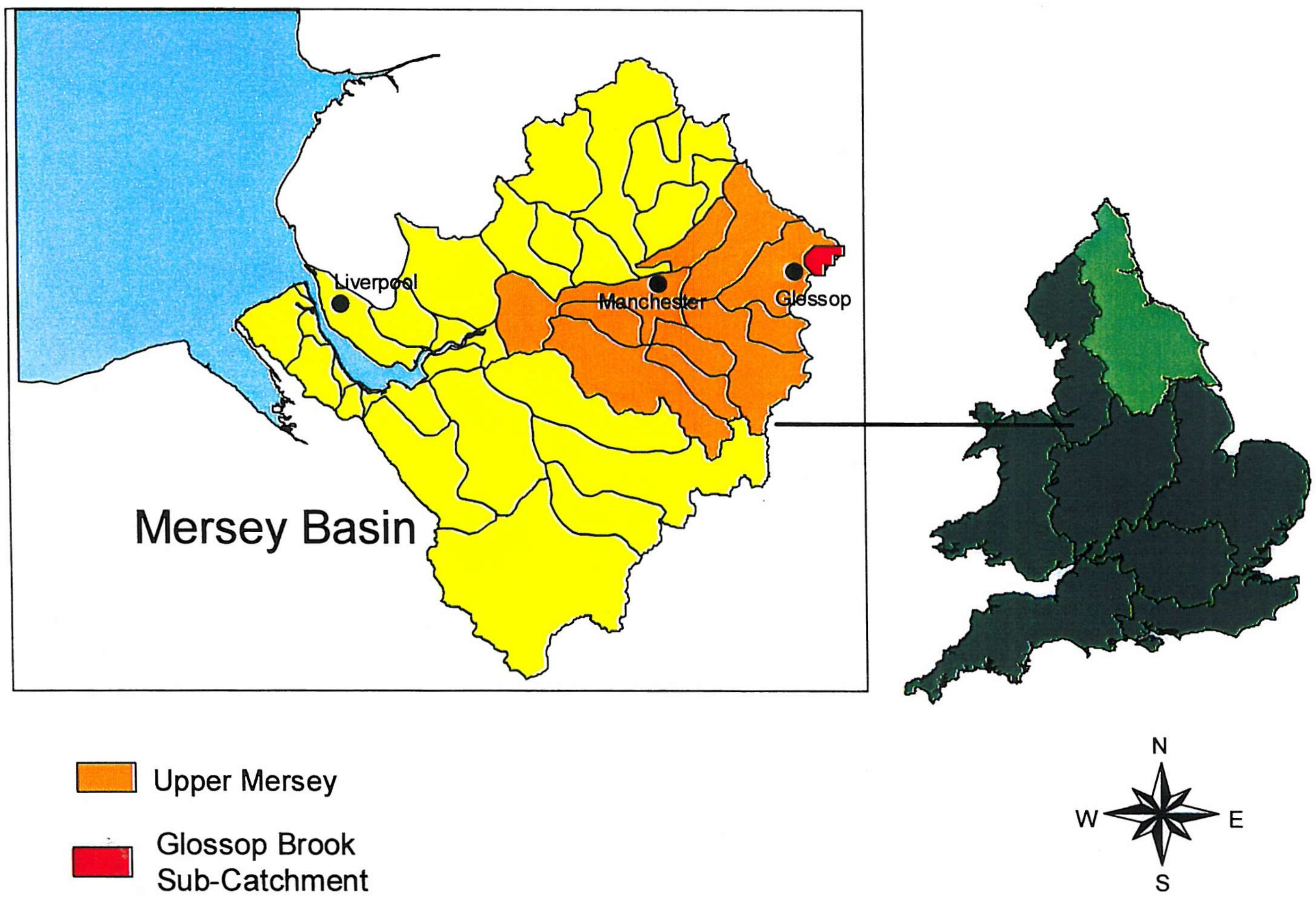
The key elements of the two case studies are presented in Table 2.1 below, the geographical locations of the sites are shown in Figure 2.1, and the studies themselves form chapters 3 and 4.

Table 2-1: Case Study Profiles Re. Research Objectives

Name of scheme to which audit approach is applied	**Main Flood Defence issues**	**Main Geomorph-ological roles**	**'Life stage' of the scheme**	**Size of catchment upstream of area in which scheme is undertaken (km^2)**
Shelf Brook	Flood Defence maintenance: control of sediment transport by use of gravel trap	Prediction of sediment-yield at trap site	Post project appraisal	15
River Mersey	Flood Defence maintenance: uncontrolled fine sediment accretion	Identifying catchment sediment sources (both natural and accelerated)	Feasibility	600

The approaches will be assessed in terms of their reliability and cost effectiveness and the need for supporting research to provide confidence in their findings. Discussions of the merits and criticisms of the approaches, and their limitations to specific Flood Defence issues, will be made.

Figure 2-1: Location of Case Studies



Chaper 3: Case Study 1 - Glossop Brook Flood Alleviation Scheme (Application To The Shelf Brook)

3.1 Flood Defence Background and Previous Geomorphological Components

The total cost of the works in the area of Glossop town centre is approx. £2.6 million. The scheme has a benefit to cost ratio of 1.17:1 (tangible benefits alone) and is designed to contain a flood of 1 in 50 year return period. Prior to the scheme (1991) an event of the design magnitude would have inundated 139 properties and 350 caravans. The project has been undertaken in 4 phases, the final one of which was completed in 1999.

A range of works have been undertaken as part of the scheme, these primarily concentrate on increases in channel capacity by widening the channel, raising flood walls and raising the soffit level of foot bridges and other obstructions. The bed was also regraded in places, weirs were removed and bedchecks installed. The primary sediment related Flood Defence issue was one of sediment accumulation in the river channels of the town centre. Such accumulation has historically served to reduce the capacity of channels and increase flood risk, therefore costly maintenance has been periodically required to remove sediments by dredging. After an initial geomorphological assessment (Sear and Newson, 1994), a gravel trap was therefore installed on the Shelf Brook in 1994 to intercept sediments before they enter the town area, and thus to prevent the accumulation of coarse sediment downstream. This work reviewed the need for, and the required size and location of the gravel trap. The study identified the Shelf Brook as the key sub-catchment in terms of sediment delivery to the design channel works in Glossop and utilised field and empirical techniques to produce a sediment budget for the lower Brook.

This sediment budget indicated the key sediment sinks and sources in the 3 km of the Brook immediately upstream from the commencement of the channel works. Additionally the technique of Hassan et al. (1993) was used to derive a range of estimated 'travel distances' for median sized sediments under a range of spate flows, effectively establishing a 'supply reach'. This information was used to locate the trap at Ordnance Survey grid reference SK 047948.

The information collected in the field was used to produce estimates of sediment volume (load) that would be produced by the supply reach and retained in the trap under a range of different flood flows. Sediment transport calculations were then applied to offer confidence limits on these estimates, (Bathurst, Graf and Cao, 1987; Bagnold 1966), and an observed sediment load from an historic flood was also obtained from documentary evidence. This information was used to calculate the required capacity of the trap, (approx. 180 cubic metres). The trap will be emptied on an 'as required' basis, but it is envisaged that this will be on a 3-5 year rolling programme.

The construction of the trap was completed summer 1995 at a cost of approx. £20,000. It comprises two rows of 'lodge stones' (or large boulders) set in a concrete apron across the channel (approx. 8 meters), which create a backwater effect encouraging deposition in their lee ('settlement zone'). 45 meters upstream is a small check-weir with a concrete apron that serves to drop the bed level locally at the head of the settlement zone, decreasing the effective gradient throughout it, and increasing the backwater effect and the tendency for deposition. The check-weir also protects the upstream limit of the trap from scour. The trap is furnished with an access ramp at the right bank abutted by a cemented boulder wall; the left bank comprises a breezeblock. (See Figure 3.1 below).

After review of the successful operation of the initial trap (Walker, 1998b), a further gravel trap was installed in 1999 on the Long Clough as originally recommended in Sear and Newson (1994).

Figure 3-1: The Newly Constructed Gravel Trap on the Shelf Brook in 1994

3.2 Flood History of the Glossop Area

The Glossop area has a long history of flooding, and there are many accounts of such events in existence, both from contemporary evidence such as newspaper reports, and from an extensive compilation of documentary and verbal evidence entitled *'The Worst in Living Memory: Great Floods in the High Peak'*, (Sharp, 1994). However, the majority of accounts pay only passing anecdotal reference to sediment-transfer.

Many of the most severe events have been attributed to convective summer storms, (Sear and Newson 1994). This includes the most severe floods on record 'the great peak flood' of 1930 and the flood of 1944, both of which have been estimated to substantially exceed the 1 in 100 year return period. The first floods in the Glossop area to be recorded were mentioned in the Anglo-Saxon Chronicles (where they serve to break up the series of pestilence and plagues noted in the area). The first dated flood occurred in 1414, the year before Agincourt, when archers practising on the butts in meadows outside the town were forced to flee as a 'tremendous deluge of flood waters inundated the fields', (Sharpe, 1994). An extensive flood history from the 18th century to date has been compiled for the Glossop area (Sear and Newson 1994), this has been extended and is presented in Table 3.1 below.

Table 3-1: Flood History of the Glossop Catchment

Date	Climatology	Documented Comments
1414	No Data	Field flooding.
1705	No Data	Field Flooding (described in the writing's of Defoe).
1711	Thunderstorm	Crops ruined many killed.
1748	Summer Flood	2 deaths, corpses from graveyard washed away (described in the journals of John Wesley).
1799	Summer Flood	1 death , bridge demolished.
1809	Summer Flood	Bakery washed away.
1834	Thunderstorm	Bog bursts and landslips gravel deposited in Glossop, extensive damage to mills, housing and roads estimated at the time by the Manchester Guardian to exceed £2,800, several people killed.
1858	Summer Flood (thunderstorm + waterspout)	Mill and four houses washed away.
1895	Thunderstorm	Bridge destroyed damage at papermill and bleachworks.
1900	Summer Flood (including waterspout)	Railway line blocked with tree-trunks and boulders.
1906	Summer Flood	10 houses and railway line inundated.
1930	Thunderstorm	'Great Peak Flood', 1 metre deep gravel deposited in Glossop, many killed, many houses and industrial properties inundated, including electricity works (£3000 damage to corporate property alone).
1932	Summer Flood	Much gravel deposited, £1000 pounds damages.
1933	Winter Flood	No data.
1937	Winter Flood	Only a few properties flooded as baseflows very low at time.
1938	Thunderstorm	Slope collapse and boulder entrainment caused 'debris wave' 2 miles long (occurred on 'glorious' 12^{th} August – shooting continued undeterred, utilising lightning flashes as illumination).
1939	Thunderstorm	Flood at Shelf Brook, bridge destroyed, damage closed Sheffield road.
1944	Thunderstorm	Largest flood on record, 6.5 inches rainfall in 2.5 hours, water depths of 15ft recorded in Glossop, estimated damage of £200,000, substantial damage to property (but less than 1930), some loss of life.
1946	No Data	Few properties flooded at Wooley Bridge.
1948	Winter Flood	No description.
1956	No Data	Few properties flooded at Wooley Bridge.

1964	Summer Flood	No data.
1965	Winter Flood	No data.
1973	Winter Flood	9 inches of mud deposited in manor park, 60 properties flooded in Glossop.
1976	Winter Flood	No data.
1986	Summer Flood	Hurricane Charlie.
1987	Summer Flood	Field flooding and minor damage to property.
1991	Winter Flood	1 in 4 year event.
1992	Winter Flood	In channel shoaling produced in Glossop town.
1996	Winter Flood	1 in 6 year event, gravel trap filled.

3.3 Catchment Characteristics

The Shelf Brook is a small upland catchment draining approximately 15 km^2 of 'Doctors Gate' area of the High Peak, (see Figure 3.2 below). It forms part of the headwaters of the River Etherow, with drains to the Goyt, which in turn drains to the Mersey. The majority of the Shelf catchment is within the Peak District National Park. The main channel flows East-West from a source at 590 mAOD (SK 096948) to form the Glossop Brook at 150 mAOD (SK 034939). As a unit the catchment comprises approximately 38% of the Glossop Brook catchment. Average annual rainfall for the catchment is 1400mm. Landuse is mixed between agricultural (rough grazing) and moorland (maintained for grouse rearing). The catchment is used extensively for informal recreation and a bankside footpath follows the Brook for much of its course. Further details of catchment characteristics are given in Table 3.2 below.

As identified in detail above, the catchment has an extensive flood history. A moderate flood event of 22 cumecs (estimated at 1 in 6 year return period) occurred during the data- gathering phase of this project on 6.3.1998, this was part of wider flooding in the Mersey basin. A summary of catchment peak flows at different return periods is presented in Table 3.3 below.

The Shelf Brook catchment is an active area of sediment production. Steep channel gradients, and high rainfall give rise to a high-energy system. Channel banks are composed largely of non-cohesive alluvial and glacial material (frequently exposed as a poorly-vegetated sandy cobble matrix). As such they are highly erodible in the most part, although occasional bluffs of bedrock and till slow erosion locally. The bed

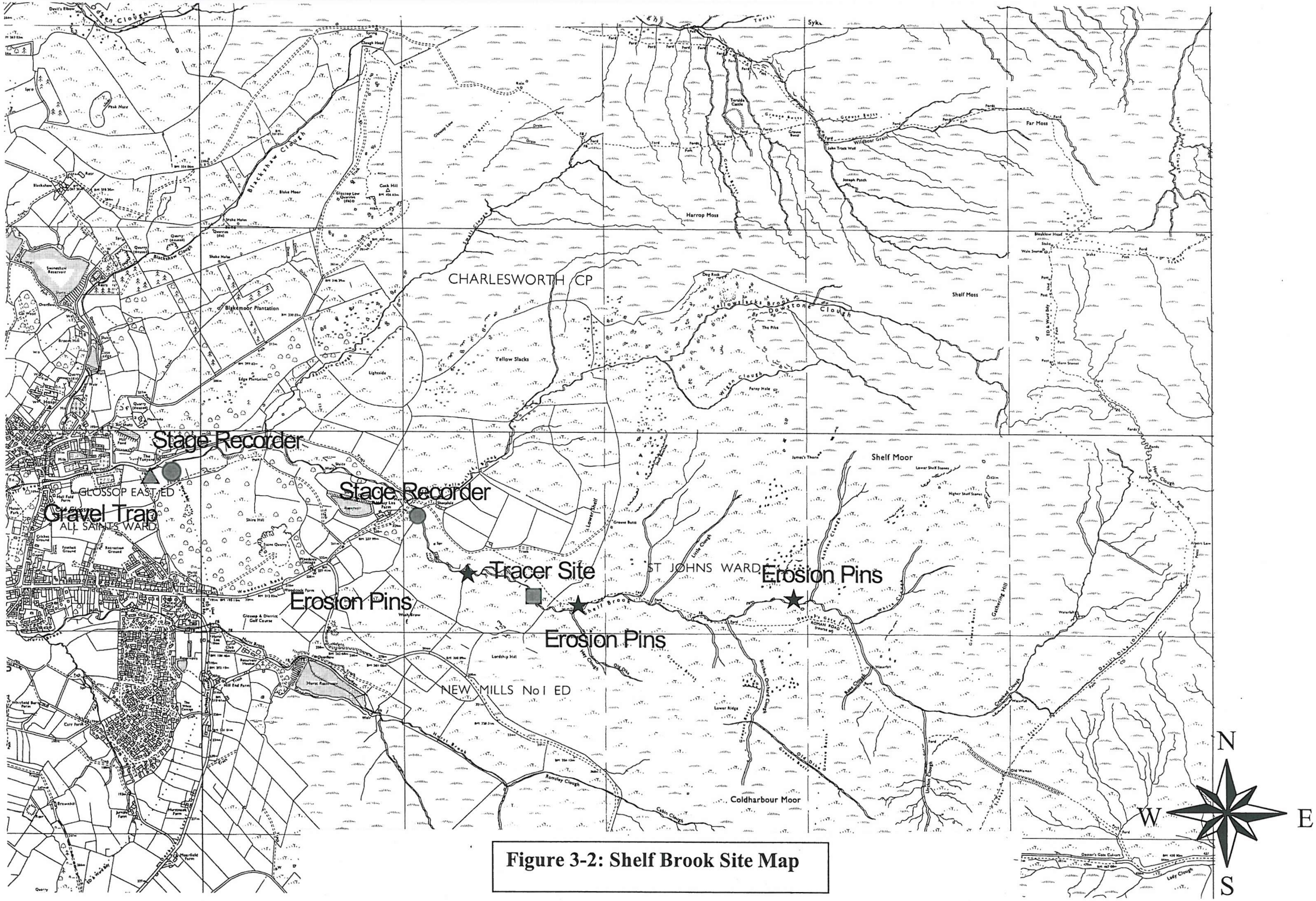


Figure 3-2: Shelf Brook Site Map

typically comprises an armoured surface layer of gravel and cobbles (median diameter 110mm), underlain by a cobble matrix containing substantial proportions of sand and gravel. Table 3.4 below gives a summary of the average particle size characteristics of bed surface material in the Shelf. The flashy nature of the catchment and the coarse nature of much of the sediment load mean that temporary storage in the channel is extensive, producing a large number of point, mid-channel and alternate bar features.

Table 3-2: Site Characteristics Summary[2]

Study Area	14.9 km^2
Mainstream Length	7.9 km
Average Slope (m/m)	0.056
Sinuosity	1.32
Principle Tributaries	Yellowslacks Brook, Shittern Clough (a.k.a. Small Clough)
Valley description	Headwaters incised, relatively steep gradient. Confined by steep walls of V-shaped valley opening in places to allow meandering on limited floodplain. Little channel modification, although widely open to stock (sheep) grazing.
Bank Stability	Sandy banks, low cohesion properties, vegetation sparse in places
Bed Stability	Mature armour layer maintained under all flow conditions excluding major spate.
Bed Texture	Surface = Cobble (see Table 3 below), sub-surface = Cobble matrix infilled with substantial quantities of sand and gravel .
Geology (Solid)	Millstone grit series, shale series.
Geology (Drift)	Recent alluvium, boulder clay, glacial sands and gravels.
Soils	Peat, stagnogleys, brown earths, alluvial gleys, stagnopodzols.
Landscape	Open moorland and rough grazing (majority of catchment falls within Peak District National Park).
Management History	Minor modifications for agricultural purposes, (e.g. few bridge crossings and ford), legacy of minor structures related to water-powered industrial production, (e.g. low weir and sluice now derelict).

2 Reference sources: Bullen and Partners (1992), and Sear and Newson (1994).

Table 3-3: Summary of Modelled Peak Flows for Shelf Brook Catchment[3]

Return Period (Years)	Estimated Flow (Cumecs)
M.A.F.	14.5
5	21.9
10	26.4
25	32.0
50	37.0
100	42.0

Table 3-4: Summary of Particle Characteristics of Shelf Brook Bed Material

Median diameter of A axis	142.5 mm
Median diameter of B (intermediate) axis	110 mm
Median diameter of C axis	45 mm
Particle Shape Classification[4]	Very Bladed

3.4 Geomorphological Objectives

This case study forms the first part of the efforts to address the objectives as defined in chapter 2 above. The objectives were to develop an audit method and demonstrate its ***versatility*** by applying it to projects in catchments with different physical habitats, catchment sizes, and flood defence management objectives and at different flood defence life-stages.

The Shelf Brook case study describes the sediment trapping management objectives of a flood defence scheme at post-project appraisal stage, in a small, predominantly upland catchment. As such it provides the opportunity to assess the appropriateness of the developing audit methods to assessing the geomorphological input to a Flood Defence Scheme 'after the event', in other words to assess, whether the audit methodology could have been successfully used to design the gravel trap, and what it can now tell us about the likely future operation of the trap.

3 Reference source: Bullen and Partners (1992).
4 According to Sneed and Folk (1958).

It also provides a chance to review the success of the audit approach in determining catchment sediment-yield (i.e. delivery of sediment to the gravel trap). In general it also provides an opportunity to assess the applicability of the audit methods to the context of a small, rural, upland catchment. It provides the first tranche in this assessment of *versatility.* The parameters of this study across the four 'test areas' of *versatility* are summarised in Table 3.5 below.

Table 3-5: Summary of the Flood Defence Objectives and Catchment Characteristics of the Shelf Brook Case Study

Different Physical Habitats	Upland catchment 200-600 m. elevation Cobble substrate Non-cohesive bank of alluvial sand / gravel, peat Sparse bank vegetation (grasses) Landuse: Sheep-grazing
Catchment Size	15 square kilometers (sq.km.)
Flood Defence Management Objectives	Sediment Trapping
Flood Defence Life-Stage	Post Project Appraisal

The study will then go on to undertake an initial assessment of the *utility* of the method, firstly by reviewing the advantages of adopting the developing audit method over existing available methods, this will include:

1. Examples of 'Geomorphological science methods' such as erosion pin measurement, particle tracing and sediment trapping / yield quantification.
2. Examples of methods of 'Geomorphological practice' including examples of existing classifications, typologies and data-collection processes.
3. Examples of methods of 'Engineering science' including comparison of the audit findings to the outputs of a range of appropriate formulae and modelling-based approaches.
4. The audit will be tested against approaches of 'Engineering practice' as part of a wider assessment of the tangible benefits of this form of geomorphological input to a flood defence design over traditional engineering methods.

(Methods of 'Geomorphological science', 'Geomorphological practice' and 'Engineering Science' have been identified and discussed in detail in Chapter 1).

Secondly the *utility* of the audit method will be tested, by identifying any significant limitations of an audit methodology based on 'rapid data-collection', and any additional data needs required to augment the audit methods in the context of this study. Thirdly, *utility* will be tested by considering the tangible benefits of the audit work, verses typical 'costs' of undertaking an audit. In conclusion generic improvements in the audit methods will then be identified and discussed.

3.5 Development of Methods

3.5.1 First approach to audit: the 'simple classification'

The main channel of the Shelf Brook and all of its principal tributaries were included in a walkover inspection, in which video evidence was collected. This material was used to devise an initial classification for the Brook, which served to split the channel into reaches based on observed geomorphological activity. (As defined in the literature review [Section 1.11.1], a classification is a system that separates reaches based on variations in geomorphological features and/or form, whereas a typology seeks to define river reaches based on variations in observed geomorphological processes). The system develops a subjective classification of channel activity, such as those of Schumm (1977) Brice (1984) and Selby (1985) amongst others. This approach considers indicators of current geomorphological activity in addition to relic features indicative of historic geomorphological activity. It produces a classification system as shown in the results section Table 3.6 and the distribution of the different reach categories is shown in Figure 3.4 below.

The classification system was based on the following parameters: sinuosity (planform) and extent of current / historical transfer features, in other words the extent to which features indicative of sediment erosion and deposition were evident in the field. These parameters were selected after an appraisal of the video material collected, as the principle factors of geomorphological variation on the Shelf Brook system. Factors of changing slope and substrate were also considered; however although there were some local variations in slope this did not stand out as a key factor initially, nor did variations in substrate, as virtually the whole Brook system downstream as far as the gravel trap comprised a medium-sized cobble bed surface. The selection of sinuosity and geomorphological features of erosion / deposition gives a classification system that is something of a hybrid between those methods which use or depend principally upon channel planform to determine channel reaches such as Leopold and Wolman (1957), Popov (1964) and to an extent Rosgen (1996), and methods that use erosion / deposition features, (or other measures of 'channel activity'), such as Schumm (1963) and Brice (1984).

The features that were taken to indicate current erosion were actively abrading channel banks and bed scour, while the features indicating historical erosion were scars and bluffs either on the existing channel course or on an historical course (indicated by terraces, exposed alluvial sediments and relic channel depressions). Features indicating current deposition were in-channel mid, side and point bars, and features of historical deposition included boulder fields, boulder berms and alluvial fans.

3.5.2 Second approach to audit: the 'multiple variable recording and analysis'

In addition to quantifying the occurrence of geomorphological features of erosion and deposition, it was also decided that a wide range of variables would be observed in order to provide data that would permit the determination of reaches on the basis of their wider geomorphological form. A wide variety of form data have previously been shown to be diagnostic of geomorphological processes (Sear et al. 1995). In-channel forms recorded included: different bedform types, barforms, and basic information on channel geometry and substrate size. The presence of any artificial structures was also recorded. Floodplain information was additionally noted such as the presence of historical depositional features (e.g. berms, boulder fields, alluvial fans and scars).

This technique sought to amalgamate the methodological approaches of the River Habitat Survey [RHS] (National Rivers Authority, 1995), the Catchment Baseline Audit, the Fluvial Audit, and elements of the Bank Assessment Record Sheet (all three methods reference: the Universities of Southampton, Newcastle and Nottingham 1997), and the Stream Reconnaissance Sheet (Thorne 1998).

None of these methods alone provided an ideal tool, as none reflected the specific geomorphological forms and processes of a small upland catchment in its entirety. The RHS contains very little floodplain information and in the Shelf Brook catchment many of the long-term sediment sources and sinks are located on the floodplain. It also does not quantify many elements that it records (noting simply 'absence / presence' or 'predominant type'). Given the size of the system (main channel length less than 8 km) it was also considered that a survey reach of 500m may not adequately delineate changes within the system, this was supported by the size of some of the smaller reaches produced by the 'simple classification' approach above (minimum 250 meters) (as shown in Figure 3.4). The Catchment Baseline Survey does not specifically record quantities and types of erosion and deposition and it also does not include detailed information on geomorphological processes on the floodplain (although it does record other floodplain elements such as landuse). The Bank Assessment Record Sheet and the Stream Reconnaissance Sheet, (as noted in Section 1.11.2), are highly detailed, extensive methods that are not intended for full catchment application. The Fluvial Audit field assessment methods come closest to fulfilling the needs of the Shelf catchment. Indeed the proforma developed for use in this case study is largely a modified version of the Fluvial Audit proforma, however specific information on geomorphological forms and features on the floodplain has been added which are relevant to an upland environment such as the Shelf catchment (e.g. Boulder-berms and alluvial fans). The method of assessing types of erosion and deposition has also been specified as estimated areas and volumes, as opposed to percentages per reach, and the method of recording has been separated into one 'set' of observations every 50 metres. Both these steps were taken to ease field recording as it was felt that in an often highly sinuous and incised riverine environment, such as the Shelf Brook, it would not be possible to always see the whole of a reach at once, and therefore the ability to record a feature as it was seen or at 50 metre intervals may be useful. The number of bed forms was additionally extended to include upland types such as steps and transverse-clast-dams. Particle size data (bed surface) was also collected for each reach using the method of Wolman (1954).

The proforma shown in Figure 3.3 below was therefore devised for field survey purposes, along with the 'Abbreviated Legend Sheet' also shown in 3.3 which was designed as an aide memorie for use in the field. This sheet defines the terminology used in the valley form, channel form, bars and bank profile section, the only other section to use abbreviations is that of bank materials where the RHS terminology was adopted (Cl, Si, S, G, Co, Be, Bo, Art, representing clay, silt, sand, gravel, cobble, bedrock, boulders, and artifical materials respectively). The main channel length was then divided into lengths of 250 meters on a 1:10000 map, and reaches were paced out and surveyed in the field. Survey commenced with reach 1 immediately upstream of the gravel trap, (as shown on Figure 3.2) All estimates of 'extent' of erosion (surface area) and deposition (volume) were estimates made by eye in the field. All of the surveyed reaches were undertaken at relatively low flows by the author during the spring / summer of 1996. Each reach took approximately 1 hour to complete, approximately 50% the time taken was used in the particle size analysis (Wolman 1954 method).

Initially it was decided to attempt to analyse the data using the TWINSPAN statistical package (part of the VESPAN multi-variant analysis suite), to derive reach types based on cluster analysis. This technique was developed for, and traditionally applied to, the identification of discrete plant communities (e.g. Furse et al. 1984). This technique has also been applied as part of the River Channel Typology undertaken by the Universities of Southampton and Newcastle (1995) and the Universities of Southampton and Newcastle (1999). Field data were taken from the completed proforma sheets and transferred to an Excel spreadsheet in TWINSPAN format. i.e. All feature names, (e.g. 'Extent of active erosion' or 'presence of minor tributaries'), were given 3 figure codes and all recorded data were expressed as a figure ranging from 0 to 100. In the case of quantified variables such as those of erosion and deposition, this simply meant identifying the maximum range for each variable within the data and dividing it by a ratio in order to produce a dimensionless 0 to 100 scale. In the case of other factors, such as valley form, where one of a number of 'types' had been recorded, each type was given an arbitrary value, with these arbitrary values equally sub-dividing the range 0 to 100. Further information on the TWINSPAN package and its use is given in Malloch (1988).

Figure 3-3: Initial Geomorphological Audit Proforma

SHELF BROOK FLUVIAL GEOMORPHOLOGICAL AUDIT

General Info.

Reach No. Survey date Photo?(No.?)
Dist. from G.T. Est. Stage at OTT

Wider Environment and Morphology

Gradient Sinuousity
Valley Form (V, C/B, St, Sy, ASy, G) Landuse - LB - RB
Vegetation (%) - Aquatic Riparian - LB - RB Trees - LB - RB

Channel Associated Features	No.	Extent of Coverage (3-D)	Est. of D50	Lichen?
Terraces				
Berm				
Boulder Fields				
Alluvial Fans				
Scars (in/active)				
Other (specify)				

No. of Tributaries - (Primary order) - Type (A-C)
No. of Tributaries - (Zero order) -
Structures in the Reach? (specify)

Sub-Reach Observation Table

	50m	100m	150m	200m	250m
Channel Form (Sy[mod], Sy[U], ASy[R], ASy[L], MB, In)					
Channel width (Bankfull, or perm.veg in gorge)					
Max depth					
10 Clast Count (+structure)					
BEDFORMS - Gen. Bed Stability					
No. of TCD					
No. of Steps					
No. of Pools					
No. of Riffles					
Bars? (P, M, BkAt, Alt)					
BANKS - Bank Materials					
- LB (Cl, Si, S, G, Co, Bo, Be, Art)					
- RB (Cl, Si, S, G, Co, Bo, Be, Art)					
Bank Profile (V, Uc, V+T, St, Gen, Comp)					
Height LB					
Height RB					
% Active Erosion LB (Length x height)	x	x	x	x	x
% Active Erosion RB (Length x height)	x	x	x	x	x
% Old Erosion LB (Length x height)	x	x	x	x	x
% Old Erosion RB (Length x height)	x	x	x	x	x
Other Features (nat.) eg. waterfalls, debris					
Other Features (art.) eg. sediment or hydrological monitoring station					

3.5.3 Third approach to audit: ' key environmental diagnostics'

This technique is a reinterpretation of the data collected in the 'second approach' above. It concentrates on quantifying 'geomorphological activity', the key processes of sediment erosion and deposition in the channel and on the floodplain. It used the information collected in the catchment proforma (as shown in Figure 3.3) and serves to expand upon the technique developed by Sear and Newson (1994) in the lower reaches of the Brook to cover the sources and sinks of the total sediment load (from the finest sands to the coarsest boulders). It was undertaken in an effort to provide geomorphological analysis that would be specifically applicable to the flood defence needs of this case study. Such developments are discussed in detail in Section 3.7 below.

3.5.4 Collection of field data using traditional geomorphological methods:

A large quantity of field data were also collected over a 2.5 year period between winter 1995/96 and Summer 1998 in parallel to the development of the audit methods. Such data encompass a variety of established techniques of geomorphological science, i.e. repeat survey of sediment accumulation in the gravel trap (to determine sediment-yield), the introduction of painted tracers, (to determine sediment transport distances for particles of different size) and the use of erosion pins to record rates of bank retreat and sediment input to the watercourse system. These data were collected as a baseline to compare the results of the developing audit methods against. This was necessary to fulfil one of the key objectives of this study, (defined in Section 2), to compare the audit methods with existing methods, (traditional methods of geomorphological science being one such area of existing methods). The field data also serve to provide 'calibration data' with which to compare some of the calculations developed from the audit work. For the sake of continuity of text, the methods and results of this work will only be introduced to the main body of this case study when direct comparisons are being made or references are being drawn (mainly in Section 3.7), however the methods used and the results obtained are detailed fully in Case Study Appendix 1: Field Data Collected For Comparison With Audit Methods.

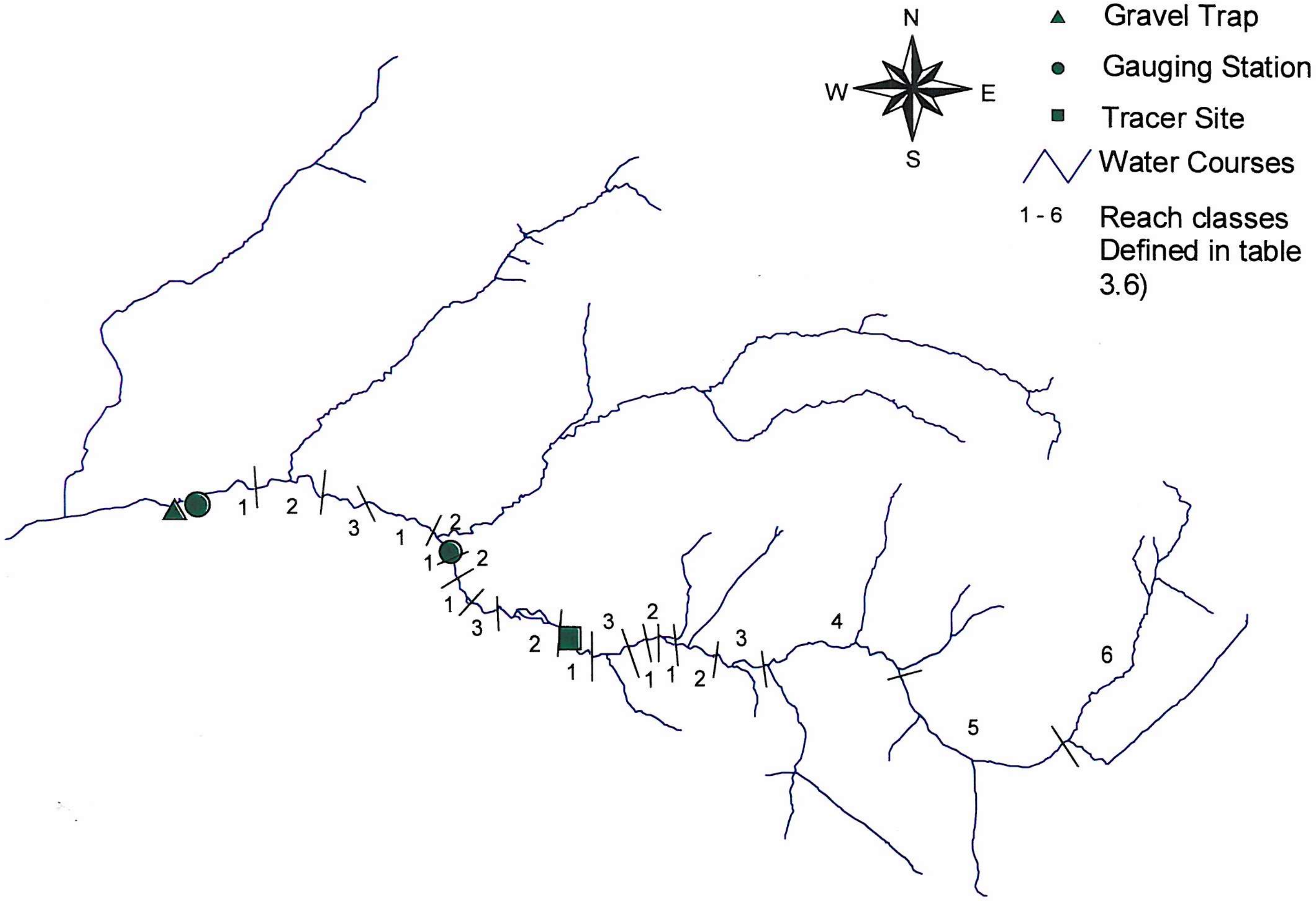
3.6 Results

The results of the initial simple classification approach to catchment audit of the Shelf Brook are shown in Table 3.6 and Figure 3.4 below.

Table 3-6: Initial Catchment Classification Using 'Simple Classification' Approach

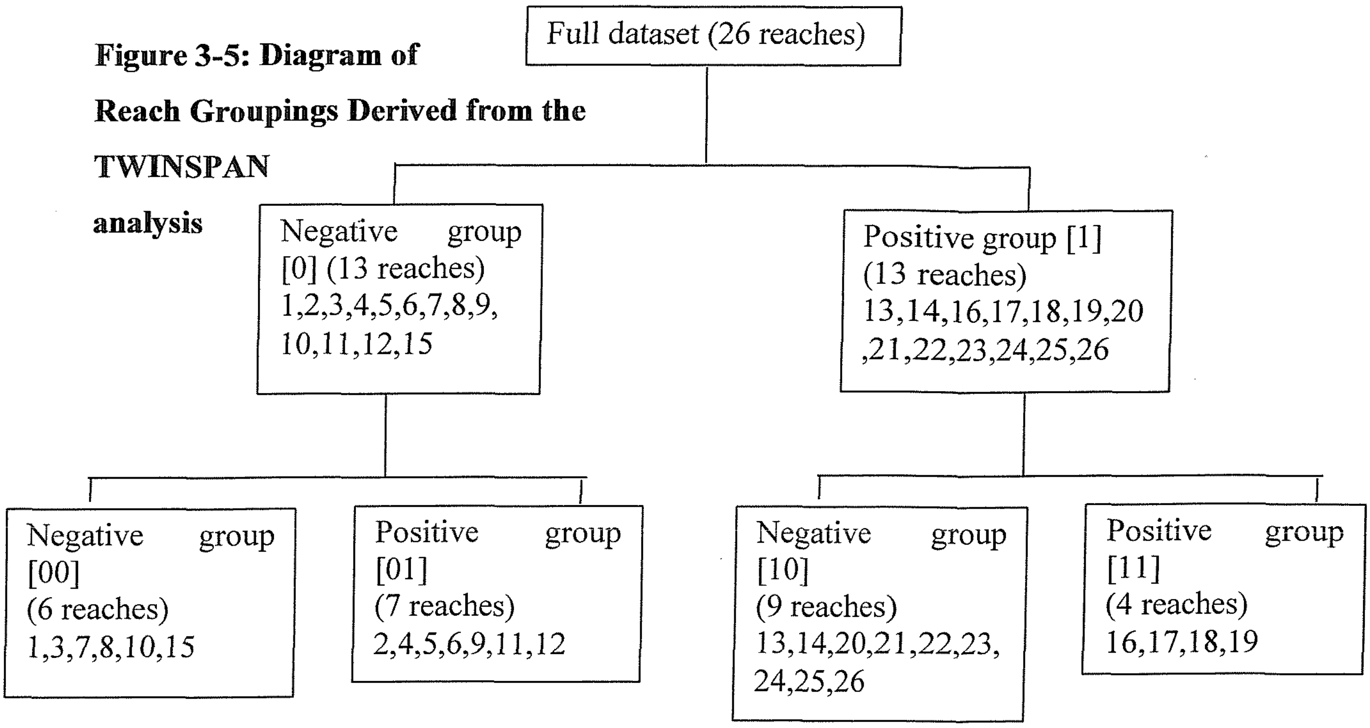
Reach Category	Planform	Extent of current transfer features	Evidence of historic transfer features	Comments	'Status'
1	Relatively straight	Minor	Minor and stable	Little current or historic erosion / deposition, what there is = vegetated / stable	Inactive
2	Moderate meandering	Minor	Major	Lots of historic erosion / deposition, now vegetated / stable	Moderately Inactive
3	Intense meandering	Major	Major	Lots of unstable historic deposition activity, current erosion activity reworking old deposition areas and working new areas	Active
4	Intense meandering	Moderate	Major	Lots of historic depositional features being reworked by current erosion	Moderately Active
5	Relatively straight	Moderate	Moderate	Bed and banks characterized by bedrock outcrops limiting activity	Moderately Inactive
6	Relatively straight	Moderate	Minor	Headwater streams incised in peat substantial fine erosion little deposition	Moderately Active

Figure 3-4: Distribution of Initial Simple Classification Reach Classes



The results of the TWINSPAN work are shown schematically in Figures 3.5 and 3.6 below, (adapting the diagramatic format as that developed in the River Channel Typology work).

Figure 3-5: Diagram of Reach Groupings Derived from the TWINSPAN analysis



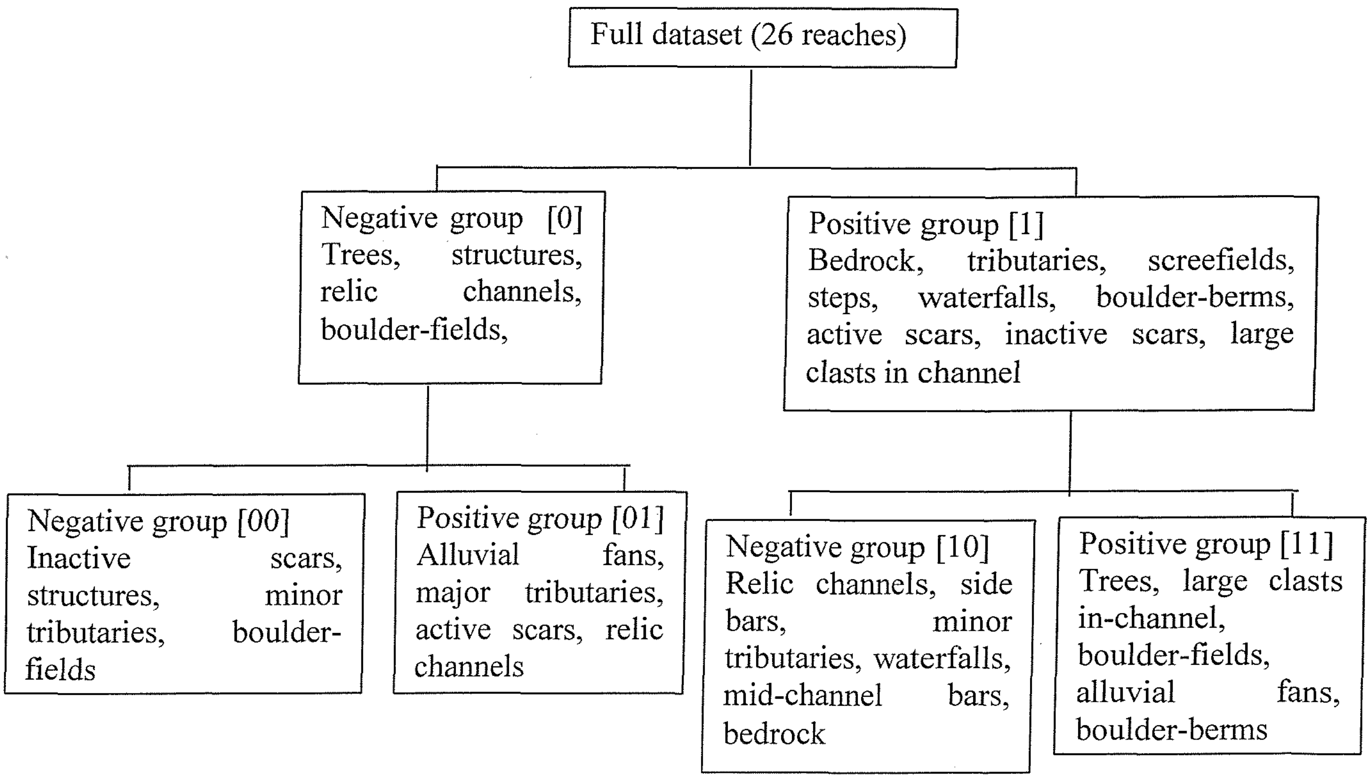
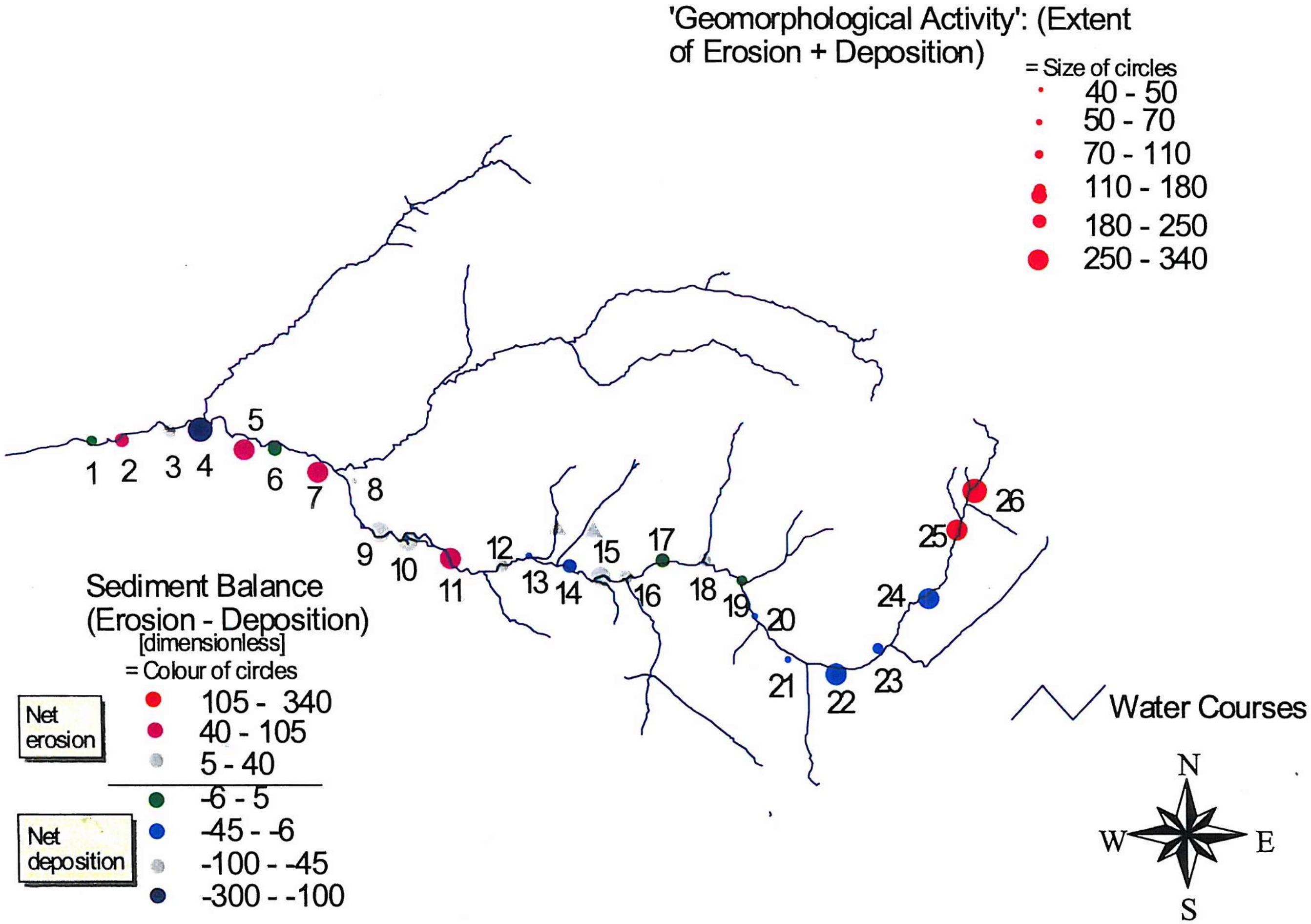
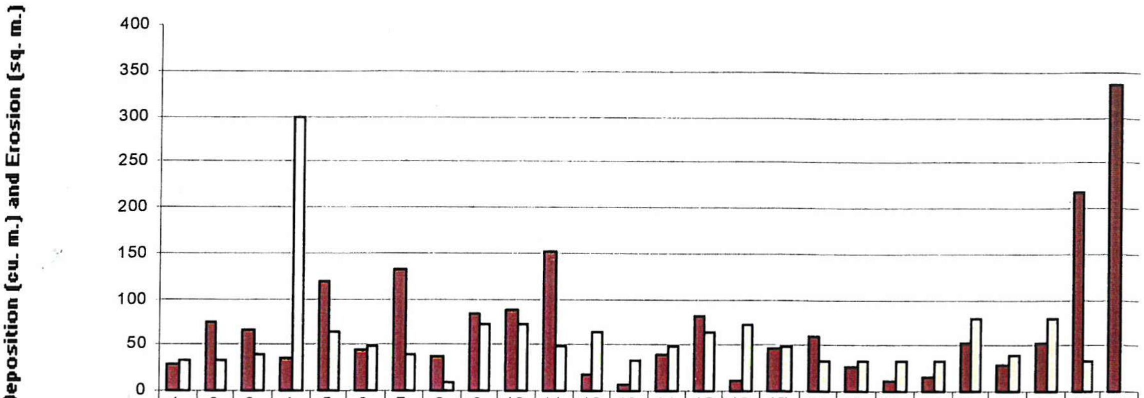


Figure 3-6: Diagram of Parameters Giving Reach Divisions Used in the TWINSPAN Analysis

Figure 3-7: In-Channel Erosion and Deposition in the Shelf Brook





	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26
Active Erosion	29	74	66	35	119	44	133	38	83	88	152	17	6	39	82	10	47	59	26	12	15	54	28	53	218	337
Deposition	32	32	40	300	64	48	40	8	72	72	48	64	32	48	64	72	48	32	32	32	32	80	40	80	32	0

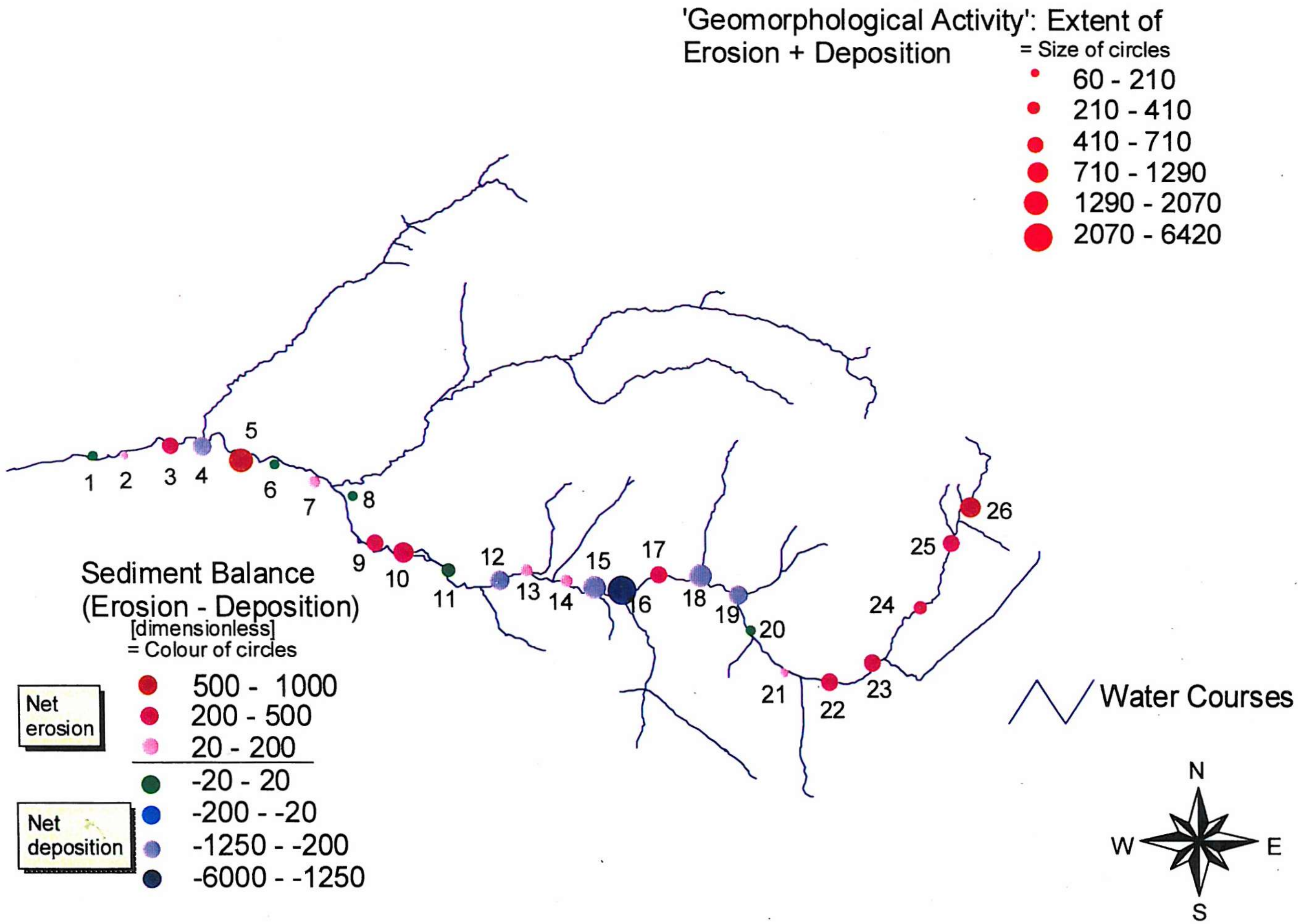
Active Erosion   Deposition

Figure 3-8: Shelf Brook In-Channel Sediments Sources and Sinks by Reach

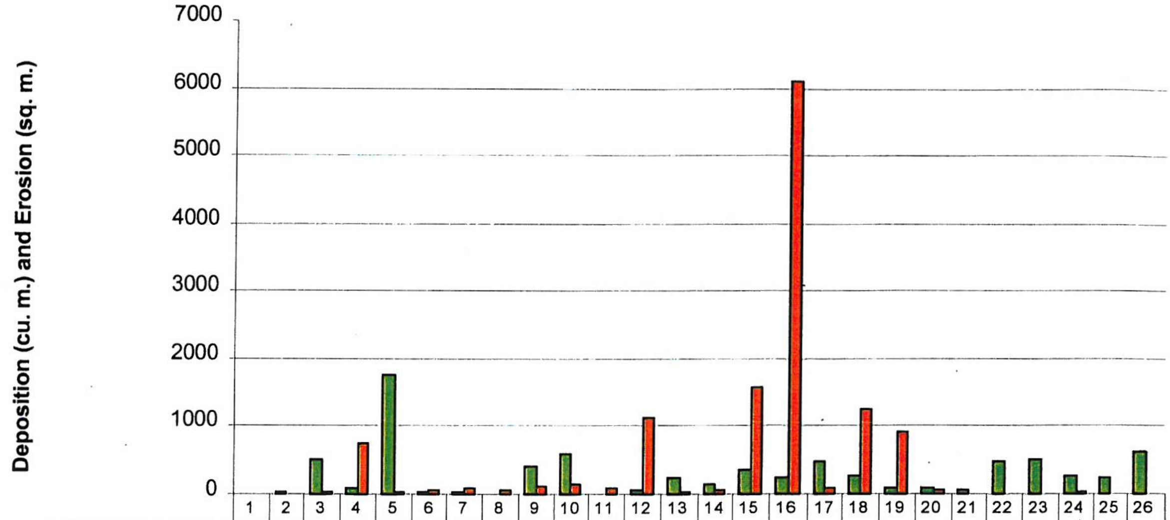
The ranges, developed in the key environmental diagnostics work, of in-channel activity, i.e. erosion *plus* deposition are shown in Figure 3.7 below, the values of in-channel erosion are determined by adding the estimated areas of 'active' (unvegetated) and 'old' (vegetated) bank erosion together. Likewise, values of in-channel deposition are determined by adding all bar volume estimates together. Figure 3.7 also gives a simple sediment balance for the reach by *subtracting* observed deposition from observed erosion, (as the units are not compatible, i.e. square and cubic meters, the scores are in the form of a dimensionless range). The values of erosion (sediment sources) and deposition (sediment sinks) are presented individually in Figure 3.8.

The ranges of activity and sediment balance for sediment sinks and sources both in the channel *and* on the floodplain ('historical' information) are shown in Figure 3.9 below, the values of erosion and deposition are presented separately in Figures 3.10 and 3.11. Data relating to features on the floodplain is termed 'historical' as they are erosion features such as scars or deposition features such as boulder-fields, boulder-berms and alluvial fans, that are not currently directly exchanging sediment with the channel system. However such features are the result of past geomorphological activity, and the derived sediment balance data includes such historical features because under a major spate event such sinks and sources would be reactivated. Sharpe (1994) provides

Figure 3-9: In-Channel and Historical Erosion and Deposition in the Shelf Brook

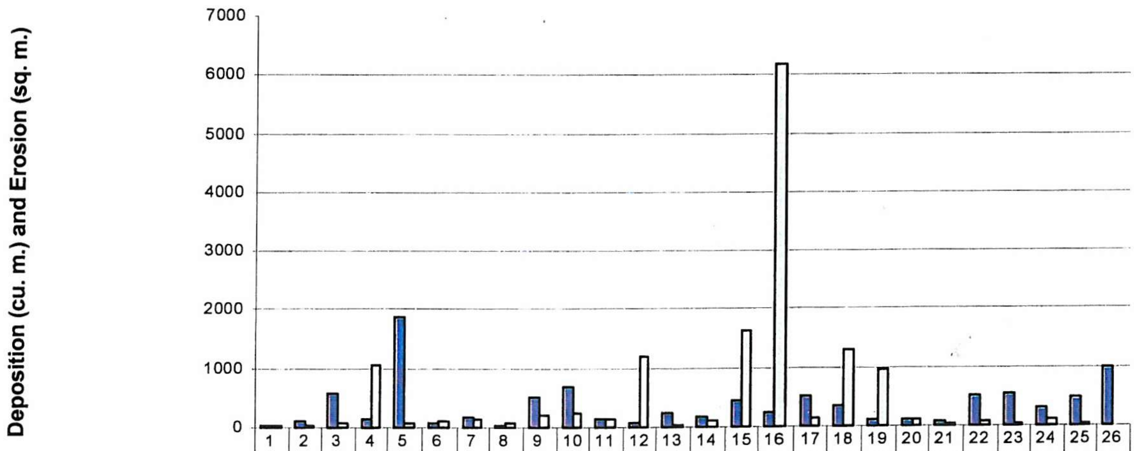


ample anecdotal evidence of such changes on the floodplain in the aftermath of large flood, and Newson (1986) provides examples from flood studies in other catchments.



	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26
Historical Erosion	0	15	50	100	175	30	36	0	430	600	0	65	235	140	350	225	462	28	90	99	70	469	508	256	250	637
Historical Deposition	0	2	30	750	20	45	101	50	125	150	100	114	15	45	157	610	96	12	938	70	0	0	0	21	0	0

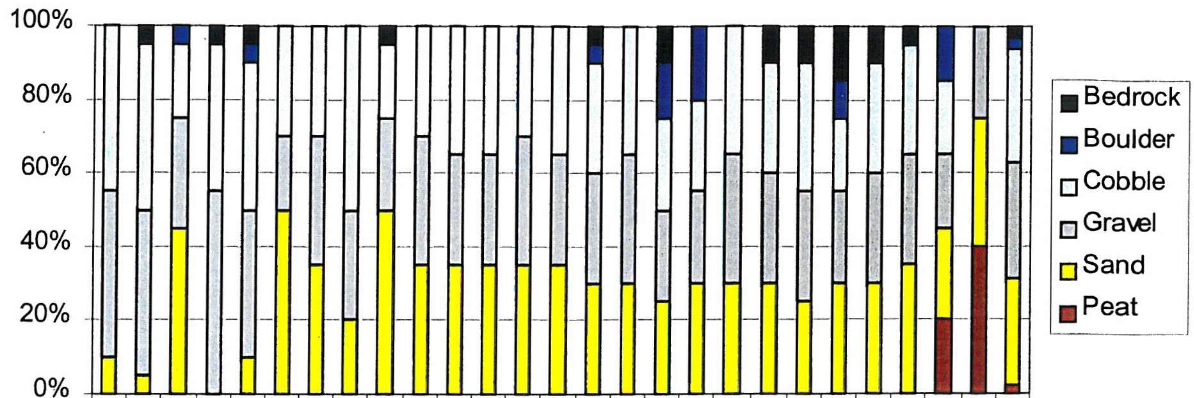
Figure 3-10: Shelf Brook Historical Sediment Sources and Sinks



	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26
Current+Hist. Erosion	29	89	566	135	186	74	169	38	513	688	152	82	241	179	432	235	50	33	116	110	85	523	536	308	468	974
Current+Hist. Deposition	32	34	70	105	84	93	141	58	197	222	148	120	47	93	163	618	14	12	970	102	32	80	40	101	32	0

Figure 3-11: Shelf Brook In-Channel and Historical Sediment Sources and Sinks

A graph of percentage sediment supply by texture, (sand, gravel, cobble etc.), is also given in Figure 3.12.



	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	Average
Bedrock	0	5	0	5	5	0	0	0	5	0	0	0	0	0	5	0	10	0	0	10	10	15	10	5	0	0	3.3
Boulder	0	0	5	0	5	0	0	0	0	0	0	0	0	0	5	0	15	20	0	0	0	10	0	0	15	0	2.9
Cobble	45	45	20	40	40	30	30	50	20	30	35	35	30	35	30	35	25	25	35	30	35	20	30	30	20	0	30.
Gravel	45	45	30	55	40	20	35	30	25	35	30	30	35	30	30	35	25	25	35	30	30	25	30	30	20	25	31.
Sand	10	5	45	0	10	50	35	20	50	35	35	35	35	35	30	30	25	30	30	30	25	30	30	35	25	35	29.
Peat	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	20	40	2.3

Reach Number

Figure 3-12: Shelf Brook Bank Materials by Reach

3.7 Discussion of Results

3.7.1 The initial 'simple classification'

This audit produced an initial overview of catchment processes, giving a good introduction to the relative locations of current and historical geomorphological activity however, the subjective nature of the observations meant that it was not possible to quantify the amounts of erosion or deposition, for instance, that were occurring, or had been occurring, in the different reaches. It was perceived at this early stage that such a subjective methodology, while it might help in identifying areas where activity was greatest, which might be useful to local field equipment for a geomorphological science (fieldwork) based assessment, was not going to produce observations that would deliver a method for estimating actual yields or rates of sediment-transfer which are required by the flood defence objectives as concerns this project (defined in Section 2). Therefore it was considered that a more comprehensive and objective data collection method was required that not only sought to consider geomorphological features on an absence / presence basis, but actually quantified the extents of such features.

3.7.2 The TWINSPAN analysis

The TWINSPAN analysis produces some interesting geomorphological conclusions. The groups negative [0] and positive [1] are simply two 'naming' categories, that is to say that the parameters described in the diagram giving reach divisions (Figure 3.6, above) pertain preferentially to each group, i.e. the occurrence of trees was significantly greater in the negative group than in the positive group. The primary split in the data are an interesting one more or less separating the upstream sites (13,14,16-26) from the downstream ones (1-12, 15). This statistically-derived split is significant in that it supports perhaps the most basic assumption of subjective geomorphological classifications, (Davis 1899, Brookes and Sear, 1997) that there is a clearly demonstrable division between the characteristics of channels in the upper and lower reaches of a catchment. Although it could be argued that the whole of the Shelf Brook catchment is essentially an 'upland area', (the downstream extent of reach 1 at the gravel trap is still at 175mAOD), meaning that there is no 'lowland' part to this catchment and that the classification therefore solely separates 'upland' or 'headwater' channel reaches from the 'middle order' reaches downstream.

This primary spilt in the classification is not made directly upon any changing hydrological, hydraulic or geomorphological index or 'driver' such as discharge, velocity or slope, but upon a series of physical features observed within the channel and on the floodplain. The physical features that are significant in giving the split in the classification at this level are, however, indirectly indicative of a geomorphological process that is perhaps the source of the different 'reach types' in the upper and lower catchment. The key process could be deemed to be changes in available energy, particularly under spate. These occur largely as a result of channel confinement, and thus conservation of energy, under spate flow conditions. This means that the downstream groups exhibit a limited floodplain or other methods by which lower energy spate environments are produced, while the upstream environments have no floodplain, and spate flows are maintained within relatively narrow (and thus high-energy) confines.

This 'energy-based split' is shown in the negative [0] (down-stream) or *lower energy group* in the significant parameters of trees, structures, relic channels, and boulder-fields. Interpretation of these parameters is as follows:

1. Trees, which will establish themselves in the vicinity of the channel only where out-of-bank flood waters are unconfined and low-energy.
2. Structures are also indicative of lower-energy spate; bridges are often built at natural fording points (which tend to be wide, shallow, and therefore low-energy channel areas). Once built they can also cause a backwater effect (ponding flows) under spate and thus reduce the energy of the waters upstream of them. Likewise weirs can lead to backwater effects and reduction in local slope, which again reduces energy.
3. Relic channels are indicative of the fact that there is enough area of floodplain to allow the significant migration of the channels and the development of such features, which will therefore give lower energy, unconfined out-of-bank flows.
4. Boulder-fields are also indicative of significant available floodplain area.

Likewise many of the significant parameters in the positive [1] group, (bedrock substrate, major tributaries, screefields, steps, waterfalls, boulder-berms, active scars, inactive scars and large clasts in the channel), are indicative of a *higher-energy group*. In this group, high-energy conditions prevail within a confined channel under spate conditions, and thus conservation of spate energy occurs. The parameters are interpreted as follows:

1. The features of bedrock substrate, steps, waterfalls and large-clasts in the channel are all indicative of a high level of in-channel energy under spate flow.
2. Boulder-berms are linear banktop deposition features, that infer the lack of a wider floodplain onto which spate flows can spill, and thus deposit their coarse sediment load over a wider area (i.e. a boulder-field).

3. Active and inactive scars are evidence of a channel that has enough floodplain to develop a sinuous course, and as that course traverses back and forth across the floodplain it strikes the valley walls at the edge of the floodplain, giving rise to such features.
4. The presence of relatively high numbers of major tributaries and screefields is perhaps indicative more of features that occur in upland environments, rather than specifically those that are relevant to the high-energy criteria.

The second-level split in the TWINSPAN classification is perhaps a little less clear in terms of what it says about geomorphological processes within the Shelf Brook catchment, in the case of the lower-energy (downstream) negative groups [00] and [01] at least. The spilt here is along the lines of the following parameters, positive group [01], (reaches 2, 4, 5,6,9,11,12): inactive scars, structures, minor tributaries, and boulder fields, negative group [00], (reaches 1,3,7,8,10,15): alluvial fans, major tributaries, active scars and relic channels. This may be indicative of some sort of split along the lines of a low-energy group with structures (possibly '*very low-energy group'*) and a low-energy group with major tributary inputs and associated features (possibly *'moderately low-energy groups*'). It is, however, hard to endorse this division as little more than speculation.

The spilt between the higher-energy groups [11] and [10] is perhaps a little clearer. The negative group, (reaches 13,14,20-26), is determined on the following parameters: relic channels, side bars, minor tributaries, waterfalls, mid-channel bars and bedrock substrate. With the exception of relic channels all of these features allude to an active in-channel environment. Whereas the positive group, (reaches 16-19) is determined on: trees, large clasts in the channel, boulder fields, alluvial fans and boulder berms. Of these parameters, trees, boulder fields, and alluvial fans are all indicative of the availability of a certain amount of floodplain. As such there is some evidence for defining two sub groups, a *very high-energy group* of 'true headwater' reaches where the channel is fully confined and geomorphological activity (under spate) is thus occurring mostly within the channel, and a *moderately high-energy group* where geomorphological activity, particularly deposition, (under spate) occurs mostly on the limited floodplain.

The results above are interesting from a point of view of a wider geomorphological understanding of the Shelf catchment, and specifically from the viewpoint that it appears possible to derive an inferred understanding of geomorphological processes under spate conditions from the geomorphological forms that may be observed under normal flow conditions using a 'rapid assessment data recording technique'. This is particularly interesting for as a small upland catchment with very limited flood defence interest upstream of the gravel trap site, the Shelf Brook does not have a network of hydrological recording stations necessary to adequately inform an accurate value of discharge for each reach. Therefore it is not possible accurately to calculate stream power directly for each reach, indeed even the empirical modeling of discharge would be largely uncalibrated for spate flows for the majority of the catchment. However, the direct calculation of spate stream power is not necessary as it appears that the geomorphological processes relating to this changing energy can be inferred from the statistically-significant presence of suits of key geomorphological forms as shown above.

Interesting as this work is from the point of view of catchment geomorphological understanding, the results of this TWINSPAN cluster analysis do not produce the sort of quantified figures of erosion and deposition per reach that are required to make estimates of yield at the gravel trap at the downstream extent of the study area. Thus they will not alone fulfill the flood defence aims of this case study. Therefore it was decided that in addition to this statistical-based analysis of the reach data, it would be necessary to undertake a specific quantification of the key 'environmental diagnostics' or erosion and deposition throughout the surveyed reaches.

3.7.3 Environmental diagnostics analysis:

The longitudinal patterns of both in-channel and historical erosion and deposition may be interpreted using the geomorphological knowledge of the catchment gained during the audit data collection. (The methods by which the values for 'in-channel' and 'historical' erosion and deposition were calculated from the audit data collected, is given in the results Section 3.6).

Such in-channel geomorphological activity may be seen to typify the conditions of sediment-transfer under flows up to bankfull in a relatively unmodified catchment such as the Shelf Brook, (Werrity, 1997). A value of '> 80 m^2 of erosion per reach', (approx. upper quartile range) was selected to identify the most active reaches in terms of in-channel erosion, as shown in Figure 3.8, and these hotspots of in-channel erosion may be interpreted as follows:

- Reaches 25, 26 - High-energy headwater sources.
- Reach 15 - Local source related to the constriction of the channel by a rising stratum of bedrock, which breaks the ground surface and forces the channel into a gorge planform. Significant erosion is related to this feature and the channel immediately downstream of it, as it creates a 'flume-type' environment under spate.
- Reaches 5, 7, 9, 10, 11 - Extended source caused by a floodplain that is locally increased in width and covered in deep deposits of coarse alluvium, into which the channel incises a sinuous, erosive course.

In-channel areas of major deposition or sediment sinks (selected as those '> 70 m^3 per reach', approx. upper quartile range), as shown in Figure 3.8 may be interpreted as follows:

- Reach 24 – Flood plain opens out fractionally allowing for some sinuosity to develop and much of the material eroded in reaches 25 and 26 to deposit.
- Reach 22 – Deposition occurs downstream of a major waterfall which gives a low gradient and low stream power locally.
- Reach 16 - Upstream of the constriction at reach 15 (described above), which probably result in a backwater effect under bankful flows.
- Reaches 9, 10 – This is probably local deposition from the sustained locally high erosion, the channel is wide here and bars giving immediate storage appear to develop close to the actively eroding bank sites.
- Reach 4 – Local deposition, well vegetated in places, which is likely to be attributed largely to the historic erosion in reach 5 upstream (see below).

These patterns of erosion and deposition indicate that in terms of a longitudinal in-channel sediment balance through the system, (as shown in Figure 3.7), the upper headwater reaches of 25 and 26 are active focuses of erosion, acting as a major sediment generation zone. The system from 19 to 24 is then characterized by net storage, while 12 to 18 presents a mix of minor net erosion and net deposition that may be seen to balance out to a zone of transport. From 5 to 11 the system is one of marked net erosion, with a major net sink then occurring at reach 4, and finally minor net erosion is seen in reaches 1 to 3. This pattern is illustrated in Figure 3.11 below.

'Historical activity' is representative of sediment source (erosion) and sink (deposition) features that, as defined in the results Section 3.6, have no direct interaction with the channel under moderate spate conditions, but are likely to be reactivated under major spate conditions (e.g. a 1 in 50 or 1 in 100 year return periods). 'Historical' values of sediment sources and sinks are shown in Figure 3.10, and the summed results of in-channel activity *and* historical activity, that may be seen to characterise total sediment sources and sinks under a major spate event are shown in Figure 3.11 above.

Historical areas of major sediment sources (arbitrarily selected as '> 400 m^2 per reach', approx. upper quartile range), as shown in Figure 3.10 can be interpreted as follows:

- Reaches 22, 23 and 26 are high-energy headwater sources, where the confined channel has no floodplain, the channel is in an incised V-shaped valley leading to development of major slope failures.
- Reach 17 is an area of localised increase in erosive power under spate, as the majority of the sediment load from the upper catchment has been deposited upstream at reaches 18 & 19.
- Reaches 3, 5, 9, 10 are areas where the meandering channel traverses across floodplain and sporadically collides with the valley walls leading to the development of major scars.

Historical areas of major sediment sinks (arbitrarily selected as '> 750 m^3 per reach', approx. upper quartile range), as shown in Figure 3.10 can be interpreted as follows:

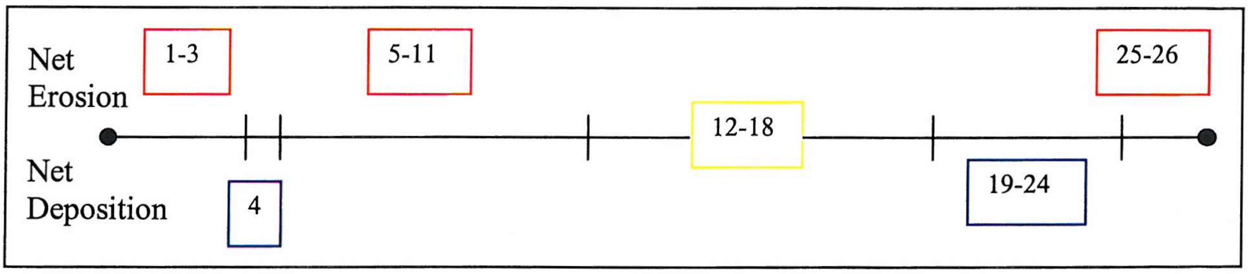
- Reaches 18 & 19 represent the first occurrence of an area of floodplain, onto which much of the sediment entrained in upper reaches is deposited.
- Reaches 15 & 16 represent a further deposition of material from the erosion in the headwater reaches and from local erosion at reach 17.
- Reach 12 is a point of local deposition from minor scars in reaches 13 and 14, and from the further deposition of headwater derived material.

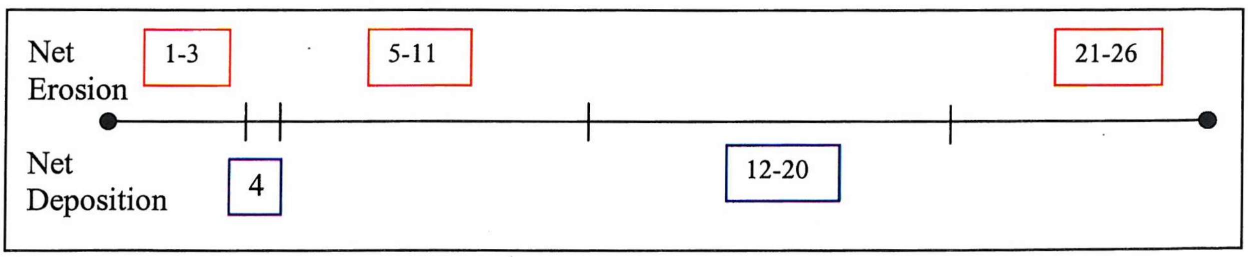
- Reach 4 is an area of local deposition largely deriving from the erosion in reach 5 upstream.

These patterns of erosion and deposition mean that in terms of a longitudinal in-channel *and* historical sediment balance through the system, i.e. net sediment-transfer under a major spate condition, (as shown in Figure 3.9), the whole of the headwaters (reaches 21 to 26) become a sediment generation zone. The channel from reaches 12 to 20 then becomes, on balance, a zone of net sediment storage. While the relative characteristics of the channel downstream from reaches 1 to 11 behave much as the net pattern for in-channel transfer, i.e. generally a zone of sediment generation, with a local sink at reach 4. The pattern is illustrated in Figure 3.13 below, and the balance of net in-channel erosion and deposition is also shown for comparison.

Figure 3-13: General Balance of Net Erosion and Deposition

In-Channel Sources





Historical and In-Channel Sources

(Boxed numbers represent reach numbers: Red = Geomorphological processes dominated by erosion, Yellow = Processes in equilibreum, Blue = Processes dominated by deposition)

3.7.4 Comparison between the different approaches:

3.7.4.1 In-channel (current) geomorphological activity

When one compares the results of the 'simple classification' audit, and the more objective findings of the 'environmental diagnostics' audit, there is some convergence in the distribution of 'hot' spots and high-activity reaches particularly in the middle reaches of the Shelf Brook. However, the qualitative visual classification of the 'simple classification' appears to underestimate activity in two ways: the significance of activity in the headwater reaches is under-played, and the role of reaches which are major active sinks, is also underestimated, (such as reaches 4 and 24). The results of the TWINSPAN analysis does not reflect current geomorphological activity, this is discussed below. The comparison between the simple classification and the environmental diagnostics audits at this level is illustrated in Table 3.7 below. For the sake of this comparison the environmental diagnostics data are separated as follows to reflect the approximate upper and lower quartile ranges:

1. Erosion scores > 80 are considered sites of major activity.
2. Erosion scores of < 30 are considered sites of minor activity.
3. Those in between sites of moderate activity.
4. Deposition scores > 70 are considered sites of major activity.
5. Scores of <40 are considered sites of minor activity.
6. Those in between sites of moderate activity.

3.7.4.2 Historical geomorphological activity

The interpretation of the TWINSPAN cluster analysis only gives statistically-significant findings in relation to geomorphological features pertaining to historical processes, i.e. geomorphological activity under major spate events. This is indicative that the Shelf Brook is perhaps a system in which, apparent (statistically significant) geomorphological change using this method, relates only to severe spate events. The reach grouping resulting from this analysis indicating geomorphological activity can, however, be added to Table 3.7 for the sake of comparison. Likewise, the simple classification results and the reach classifications of the environmental diagnostics

Table 3-7: Comparison of Perceived Geomorphological Activity in Shelf Brook Catchment Using Three Audit Methods

Reach Numbers	Simple Classification				TWINSPAN Cluster Analysis				Environmental Diagnostics			
	Historic Activity		*In-channel (Current) Activity*		*Historic Activity*		*In-channel Activity*		*Historic Activity*		*In-channel Activity*	
	Er	Dep	Er	Dep	Er	Dep	Er	Dep	Er	Dep	Er	Dep
1	Min	Min	Min	Min	Min	Min			Min	Min	Min	Min
2	Min	Min	Min	Min	Min	Min			Min	Min	Mod	Min
3	Maj	Maj	Min	Min	Min	Min			Maj	Min	Mod	Min
4	Maj	Maj	Min	Min	Min	Min			Mod	Maj	Mod	Maj
5	Maj	Maj	Maj	Mod	Min	Min			Maj	Min	Maj	Mod
6	Maj	Maj	Maj	Mod	Min	Min			Min	Min	Mod	Mod
7	Maj	Maj	Maj	Mod	Min	Min			Min	Mod	Maj	Min
8	Min	Min	Min	Min	Min	Min			Min	Min	Mod	Min
9	Maj	Maj	Maj	Maj	Min	Min			Maj	Mod	Maj	Maj
10	Maj	Maj	Maj	Maj	Min	Min			Maj	Mod	Maj	Maj
11	Min	Min	Min	Min	Min	Min			Min	Mod	Maj	Mod
12	Maj	Maj	Maj	Maj	Min	Min			Min	Maj	Min	Mod
13	Min	Min	Min	Min	Maj	Maj			Mod	Min	Min	Min
14	Maj	Maj	Min	Min	Maj	Maj			Mod	Min	Mod	Mod
15	Maj	Maj	Maj	Maj	Min	Min			Mod	Maj	Maj	Mod
16	Mod	Maj	Mod	Mod	Mod	Maj			Mod	Maj	Min	Maj
17	Mod	Maj	Mod	Mod	Mod	Maj			Maj	Mod	Mod	Mod
18	Mod	Maj	Mod	Mod	Mod	Maj			Mod	Maj	Mod	Min
19	Maj	Maj	Mod	Mod	Mod	Maj			Min	Maj	Min	Min
20	Mod	Mod	Mod	Mod	Maj	Mod			Min	Mod	Min	Min
21	Mod	Mod	Mod	Mod	Maj	Mod			Min	Min	Min	Min
22	Mod	Mod	Mod	Mod	Maj	Mod			Maj	Min	Mod	Maj
23	Mod	Mod	Mod	Mod	Maj	Mod			Maj	Min	Min	Min
24	Mod	Mod	Min	Min	Maj	Mod			Mod	Min	Mod	Maj
25	Mod	Mod	Min	Min	Maj	Mod			Mod	Min	Maj	Min
26	Mod	Mod	Min	Min	Maj	Mod			Maj	Min	Maj	Min

approach for historical activity can also be added to Table 3.7. For the sake of this comparison the environmental diagnostics data are separated as follows to reflect the approximate upper and lower quartile ranges:

1. Erosion scores > 400 are considered sites of major activity.
2. Scores of <100 are considered sites of minor activity.
3. Those in between sites of moderate activity.
4. Deposition scores > 750 are considered sites of major activity.
5. Scores of <50 are considered sites of minor activity.
6. Those in between sites of moderate activity.

When comparing the qualitative historical geomorphological activity results of the simple classification to those of the quantitative results of the environmental diagnostics approach, it is evident that there is a relative over-estimate of the consistancy of major geomorphological activity (both erosion and deposition) in the lower reaches (e.g. 3-7). In the upper reaches (e.g. 20-26) there is tendency to over estimate the significance of deposition and under estimate the significance of erosion. The are many similarities in the middle reaches, the most striking contrast being the over estimate of both erosion and deposition activity at reach 14.

A comparison of the TWINSPAN approach and the environmental diagnostics approach is slightly less straight forward. The statistical derivation of the former offers a model in which only 4 groups of reaches are identified, as discussed above, therefore the expression of geomorphological activity across the 26 reaches under 'historical' conditions is somewhat simplified. However, the basic statistical divisions that are made in the TWINSPAN approach can also be observed in the environmental diagnostics approach. If one interprets the environmental diagnostics data using the same reach divisions and geomorphological reasoning the first key TWINSPAN division using the environmental diagnostics data, i.e. the split into lower energy groups (reaches 1-12 &15) and higher energy groups (reaches 13,14 &16-26), then it is clear that a similar pattern is apparent. There is 40% more geomorphological activity occurring in the high-energy group of reaches (combined scores for erosion areas plus depositional volumes of 13,800 / 9800). Also if one takes a similar approach to testing the division of the TWINSPAN high-energy groups into the 'high-energy group (dominated by in-channel processes)', [reaches13,14,20-26] and the 'moderately high-energy group (which exihibits floodplain deposition)', [reaches 16-19] then it is evident from the environmental diagnostics data that the latter group is responsible for almost 30% of the historical deposition in the whole data set of 26 reaches (4050 / 14090 cubic metres).

What does the interpretation of the three approaches to geomorphological audit above tell us? Firstly, it indicates that a qualitative method of classification may convey the overall pattern of geomorphological activity within a catchment, but it is unlikely to identify the detailed processes of erosion and deposition accurately. Secondly, it shows that it is possible to derive a reach classification, using statistical method, that is applicable to geomorphological processes. However such a method is comparatively coarse in its derivation of reach groupings and it appears to centre on geomorphological processes which occur under major spate events. Thirdly, it has been shown that it is possible to derive a reach classification that shows similar basic patterns of geomorphological activity to the statistically derived model; however it concentrates purely on the interpretation of the environmental diagnostics of sediment-transfer (i.e. the extent and distribution of erosion and deposition). The next challenge is to apply the audit results to the flood defence objectives of the project.

3.7.5 Applying the results

The results above can be seen to describe geomorphological activity within the study catchment under existing (moderate) flow conditions and historical (extreme event) conditions. With an eye towards application, and flood defence management requirements, the question must however now be asked, 'could the audit results have been used to estimate the total sediment load arriving at the gravel trap?' Or in other words, could the audit method developed have been used to design the required capacity of the trap?

The audit may be used to derive a catchment sediment-yield (per annum) at the gravel trap in the following way. The yield of fine sediment may be considered to be derived from all the fine proportion of the actively-eroding sources in the catchment. Reference to basic texts on particle size entrainment, (for example the early work of Hjulstrom, 1935), illustrates that particles finer than 2 mm are entrained at a velocity of approximately 0.1 m/s. Observations from the Shelf Brook on any day of the year confirm that such velocities are exceeded at the vast majority of sections. (Velocities in the range 0.5 – 2 m/s were recorded during the rating work at the gauging stations, described in Case Appendix 1). Therefore the fine sediment-yield might be estimated from the following:

The total surface area of 'in-channel active erosion' (as shown in Figure 3.8) = 1860 square metres. This may be developed into an estimated volume by using a simple method for estimating a rate of bank retreat. Such a method is the relationship between erosion rate / drainage basin area, presented in Thorne, Hey and Newson (1997), (shown in Figure 3.14 below), which gives an erosion rate of approximately 0.1m. p.a., and thus a total volume of sediment delivered, (of all particle sizes), of 186 cubic metres p.a.

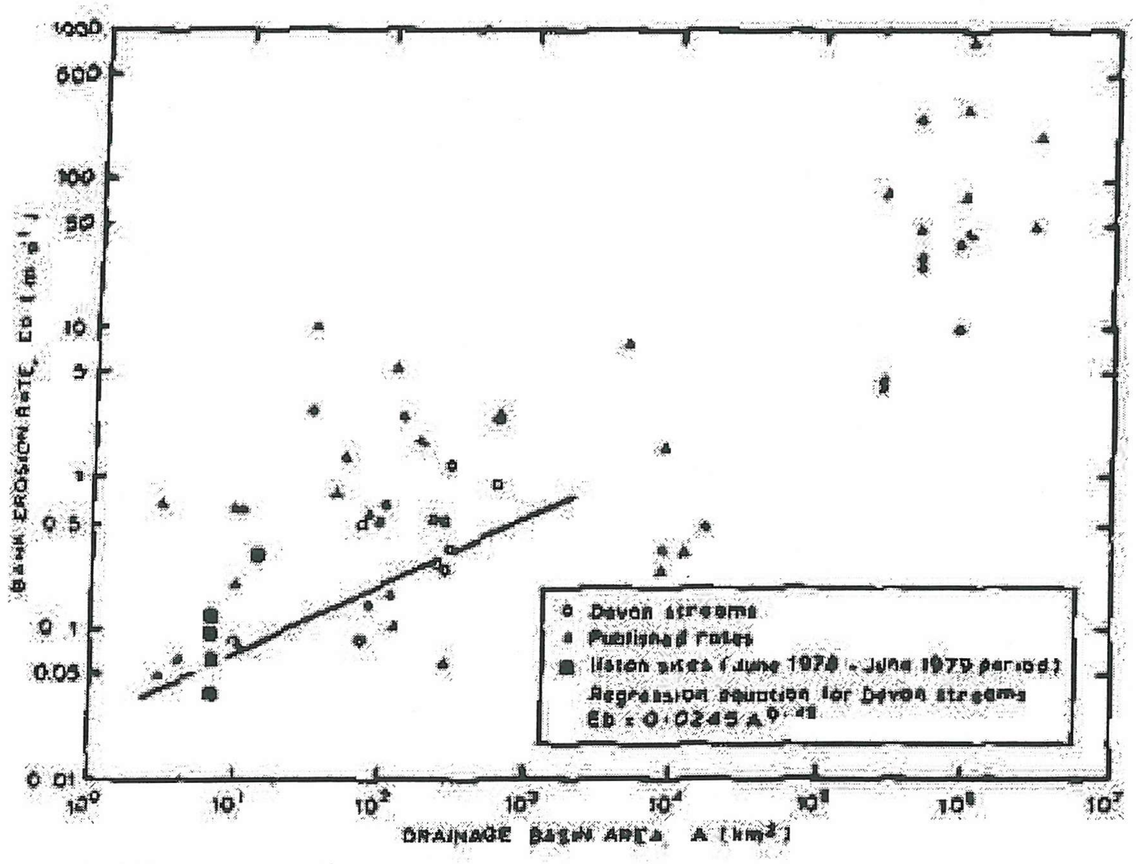


Figure 3-14: Typical Erosion Rates by Catchment Area

(After Thorne, Hey and Newson, 1997)

From the audit information (Figure 3.12) it may be seen that approximately 29% of the recorded active erosion is producing fines (classed as sands in the Figure 3.12). This gives 54 cubic metres (143 t) p.a. fine sediment-yield.

It is also possible to estimate the coarse sediment-yield from the audit results, with the aid of a few basic pieces of information readily available from hydrological textbooks and appropriate geomorphological literature. Firstly, coarse sediments will not be delivered to the trap from the whole catchment within the timescales applicable to flood defence maintenance. The question remains: how far will they travel within a timeframe of a few years?

Reference to sediment transport observations in similar environments to the Shelf Brook, such as Carling (1983) and Sear (1996), illustrate that only 'reach 1' in the audit, (i.e. the 250 meters upstream of the trap), is likely to supply any coarse sediment within this timeframe. This gives a Figure of recorded deposition (supply potential of coarse sediments) of 32 cubic metres. But how long might it reasonably be expected to take for this coarse sediment to move into the gravel trap?

Might it be expected that all this coarse material would be delivered to the gravel trap by a bankful flood? (Expected to occur in undeveloped catchments under 'mean annual flood' conditions – once in 2.3 years, Shaw 1988). The audit information for reach 1, in conjunction with simple hydrological calculations, (Shaw, 1988), may be used to test this. Average bankful width (w) is 6.5 metres, average bankful depth (d) is 1.2 metres and average bed slope (S) is 1 in 40 (0.025). Therefore, in approximate terms the wetted perimeter (P) is 8.9 (2d+w) and the area (A) is 7.8 square metres (dw). Therefore the hydraulic radius (R) is 0.88 (A/P). Discharge (Q) for the bankful flood may then be calculated as 18.8 cumecs using:

$$Q = AV, \text{ when } V = {}^{1}/n\, R^{2}/_{3}\, S^{1}/_{2}$$

(Where: V= velocity, and n = manning's roughness, taken from Chow, 1959, to be 0.060). In this case a modelled value of 14.5 cumecs is available for the Shelf Brook in the vicinity of the gravel trap (as shown in Table 3.3 above). However the value derived from the simple calculations here will be used to illustrate how the overall methods might be applied to any site, modelled or not.

This figure for bankful discharge may be converted to a figure for bankful stream power (ω) of 547 watts / square metres, where ($\omega = \rho\gamma QS / w$), (Where: ρ = acceleration due to gravity [taken as 9.81] and γ = specific weight of water [1000]). Reference to Thorne, Hey and Newson, (1997), (shown in Figure 3.15 below), indicates that at this stream power particles in excess of 170mm will be transported. The particle size information collected as part of the audit indicates that this includes virtually all of the coarse material deposits in reach 1.

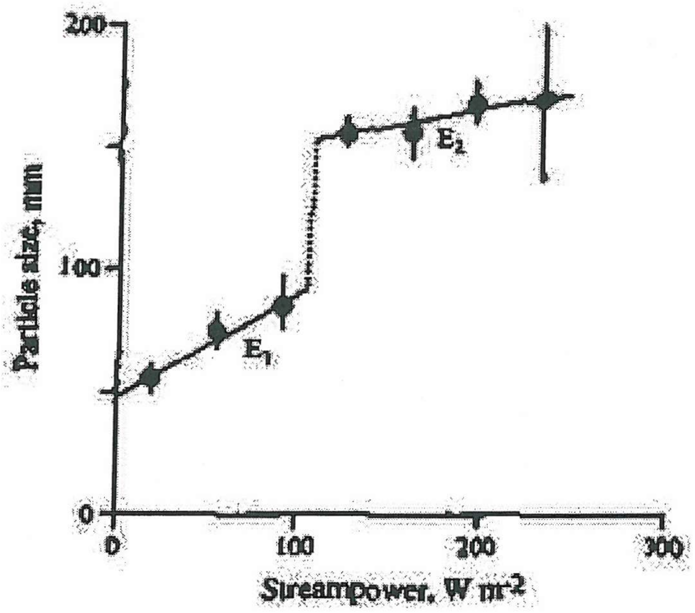


Figure 3-15: An Example of the Relationship Between Stream Power and Sediment Entrainment

(After, Thorne Hey and Newson, 1997)

Therefore it is not unreasonable to suggest that, using the audit results it may be shown that all of the 32 cubic metres (84.8 t), of coarse material recorded as deposited in reach 1 may be delivered to the trap within 2.5 years, [averaging to 12.8 cubic metres (33.9 t) per year], and that 54 cubic metres (143 t) of fine sediment may be delivered in one year. So in answer to the question *could the audit results have been used to inform the design of the gravel trap?* The answer is a cautious yes – the trap must be designed to retain approximately 35 tonnes per year of coarse sediments and approximately 150 tonnes of fine sediment, (depending on the trap design, much of this may be 'flushed' from the trap under spate flows).

3.7.6 Comparing the results to the geomorphological objectives

It is now possible to compare the results above to the objectives as defined in chapter 2 of the case study. These objectives focused on testing the *versatility* and *utility* of the audit approach.

Addressing first the aspects of *versatility,* this case study shows that the audit method can be applied to the following physical habitats: a relatively high-energy, upland catchment, with varying sediment types (substrate and bank materials) from sands to boulders. The study also illustrates that the audit can be used successfully in a relatively small catchment.

The discussion in Section 3.7.5 shows that the audit developed in this case study can be successfully applied to geomorphological role, defined in Table 2.1, of predicting sediment-yield re. the flood defence objective of sediment trap provision. Can the audit also be used to give any added 'value' to this flood defence scheme at the 'life-stage' of post-project appraisal?

The audit can be used to compare the estimated annual sediment-yield at the trap to the original design capacity and intended maintenance interval. In this way it can be used as a post-project appraisal tool. The trap capacity is approximately 180 cubic metres, (adequate to contain approx. 477 tonnes of sediment), and the maintenance schedule was envisaged as once every 3 to 5 years. The audit results estimate that a combined (coarse and fine) sediment load of approx. 185 tonnes per year will be delivered to the trap. The audit thus shows the trap design, and its maintenance program, to be of approximately the correct capacity / frequency, particularly given the 'leaky' design of the trap for fine sediments.

Concentrating on aspects of *utility* a number of key questions may be answered.

Any advantages of the audit method over existing methods will first be considered.

1. Methods of engineering practice, as discussed in Section 1.7.2, in the case of a sediment-yield problem to an area of urban flood risk would tend to adopt a traditional approach to amelioration such as dredging. It is difficult directly to compare the advantages of the audit method to such traditional practices; however, efforts will be made to make such a comparison in the next case study. If a gravel trap was constructed then it would be designed using simple methods of engineering science, such as sediment-yield formulae, the audit method will be compared with such methods below.

2. In terms of methods of geomorphological science, as already noted in Section 1.10, field data collection is time consuming and expensive. It has been shown above that it is possible to do a 'quick and dirty' extrapolation from the audit results to derive likely sediment load information to inform gravel trap design, with the use of some typical values from the literature. How accurate are the results of the audit approach compared to the detailed field data collected over several years?

   Results collected using traditional geomorphological methods: As outlined in Section 3.5, above, the full results of the trap accumulation monitoring, tracer work and erosion pin records collected for comparison to the audit results are detailed in Case Study Appendix 1: Field Data Collected For Comparison With Audit Methods.

   However, Table 3.8 below gives a broad summary of the findings of this work:

Table 3-8: Summary of the Results of Field Work in the Shelf Brook Catchment

Measurements of sediment retained in Gravel Trap		
Total over 2.5 yrs. in tonnes, & *[cubic metres]*	Quantity attributed to single moderate flood event, 1998. in tonnes, & *[cubic metres]*	
332 *[125]*	247 *[93]*	
Estimated quantities of suspended and bedload material retained in gravel trap over 2.5 yrs		
Suspended sediment (tonnes)	Bedload (tonnes)	
103 (31%)	229 (69%)	
Observations of tracer movement over 2.5. years		
Maximum distance moved (m.)	Average distance moved (m.)	
124	16.7	
Erosion pin measurements over 1 year		
Min. recorded erosion (mm)	Av. recorded erosion (mm)	Max. recorded erosion (mm)
35	100	175

The extrapolated audit results presented in Section 3.7.5 above could not be used to estimate sediment transport rates (corresponding to tracer movement in the Table 3.8), or bank erosion rates (corresponding to erosion pin measurements in the Table 3.8). Such rates are simply not observable using a 'one-off' site assessment such as the audit method. However, it was shown that, with the use of readily available methods from the wider pool of geomorphological and hydrological literature, it is possible to estimate such rates and to extrapolate a sediment-yield at the gravel trap. The extrapolated figure of approximately 85 tonnes of coarse sediment over 2.5 years is close to the observed figure of 103 tonnes shown in Table 3.8 above. While the extrapolated figure for fine sediment-yield of approximately 143 tonnes per year (equating to 358 tonnes over 2.5 years) is higher than the observed figure of 229 tonnes shown in Table 3.8 above, the extrapolated figure assumes retention of all fine sediment in the gravel trap. The trap is however designed to 'leak' fines under spate flows to increase its storage potential. The full sediment-yield observations in Case Appendix 1 show that under the first 6 months of operation no significant spate flows occurred at the trap, and therefore it served to retain all fine sediments. The quantity of fines retained over this period was 95 tonnes (equating to approximately 475 tonnes over 2.5 years if total trapping is assumed).

In summary, the audit methods produced estimates for coarse sediment-yield over 2.5 years of trap operation that were within 21% (underestimate) of the observed yield, (103t / 85t). For fine sediments the audit method produced results that were within 33% (underestimate) of the observed yield over the same 2.5 year period (475t / 358t). Within the context of geomorphological endeavor this means that the audit method could be considered relatively accurate at predicting sediment-yields. The principle advantage of the audit method over such 'geomorphological science' or field methods is that it takes about 1 hour per reach to collect the information in the geomorphological audit, as opposed to 2.5 years to amass the field data collected in this case study. In the course of the design phase of a flood defence project the turn-around time for geomorphological information is months at most, more often weeks, therefore the audit methods have a clear advantage over traditional methods of 'geomorphological science' in this respect.

3. How do the estimates of yield using the audit method compare to other existing methods? In terms of methods of 'Engineering Science' (formulae), Table 3.9 below gives estimates of yield, from the Bagnold (1966) and Bathurst et al. (1987) formulae which are appropriate to upland gravel/cobble bed river systems such as the Shelf Brook (as used in the original design of the gravel trap discussed above Section 3.1, the method is presented in Figure 3.16 below), and also from the Scholitch (1934) and Meyer-Peter and Muller (1948) methods. Such formulae methods assume a continuous and unlimited supply of sediment, and are only suited to the derivation of yield estimates over periods where sediment supply is likely to be continuous, such as during a discrete flood event. Therefore, the estimates in Table 3.9 are given for a single 22 cumecs flood event. Such an event occurred on the Shelf catchment in 1998 and a figure of gross sediment-yield at the gravel trap of 93 cubic metres of sediment was recorded. However, this yield is a gross estimate as it attributes all the sediment from the preceding year to that one large event. It can clearly be seen that the four 'engineering science' methods presented overestimate yield at the trap to a greater or lesser extent, even within the confines of the operation of the trap over a single event. Nevertheless, it should be noted that the Bagnold method does not vastly over estimate. This is most likely attributable to the fact that even under spate event conditions sediment supplies are

not unlimited. The inaccuracies, to a greater or lesser degree, of such methods over short spate events implies that the 'engineering science methods' are not well suited to estimates of sediment-yield over much longer periods of time required to deduce useful flood defence maintenance information. On the other hand, the audit method developed in this case study has been shown (above) to give reasonable long-term estimates. Therefore the audit method has clear advantages of such methods.

Table 3-9: Estimates of Yield at Gravel Trap Under a 22 Cumec Spate Event (Engineering Science Methods)

Method	Type of Method	Yield (cubic metres)
Recorded Accumulation	*Geomorphological Science*	*93*
Bathurst et al. (1987)	Engineering Science	520
Bagnold (1966)	Engineering Science	120
Meyer-Peter and Muller (1948)	Engineering Science	292

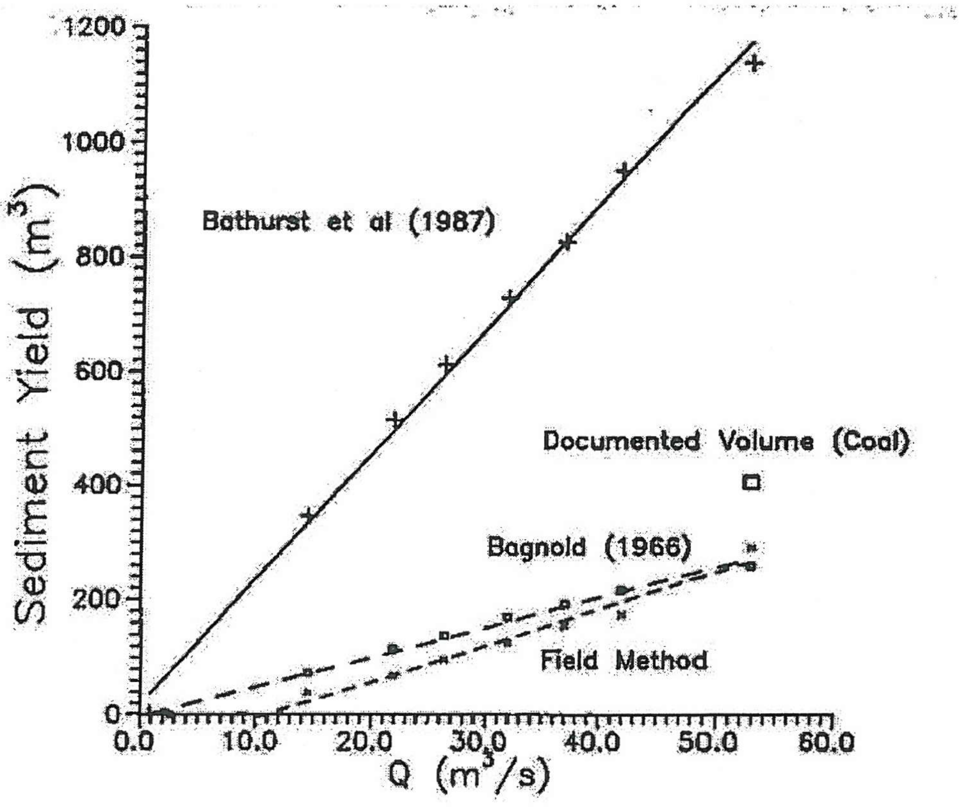


Figure 3-16: Estimates of Yield at the Shelf Brook Gravel Trap

(After Sear and Newson, 1994).

All formulae are given in Case Appendix 2, the derivation of the methods of Bathurst et al. and Bagnold are shown in Figure 3.16 above.

4. The audit method of this study can also be compared to the existing methods of 'Geomorphological Practice', firstly in the form of the 'field' method developed at the Shelf Brook site by Sear and Newson (1994) (as described in Section 3.1 above) and Newson's (1986) generic catchment yield work. The findings of these methods when applied to the Shelf Brook at appropriate timescales, (i.e. A single flood event and an average yield per year), are shown in Table 3.10 below.

The Sear and Newson (1994) method uses an empirical basis for initially estimating sediment-yield, but modifies such estimates using: 1. the Hassan et al. (1993) method to give supply reaches, and 2. field survey to assess quantities of sediment supply and storage.

Table 3-10: Estimates of Yield at Gravel Trap (Comparison of Geomorphological Practice Methods to Geomorphological Science)

Method	**Type of Method**	**Yield**	**Period**
Recorded Accumulation	*Geomorphological Science*	*93 cubic metres*	*Single 22 cumec event (gross est.)*
Field method, (Sear and Newson 1994), derivation shown in fig. 3.16 above	Geomorphological Practice	70 cubic metres	Single 22 cumec event
Recorded Accumulation	*Geomorphological Science*	*190 t fines, 42 t coarse*	*Average per year*
Catchment Yield Method (Newson, 1986), [av. Yield p.a.], derivation show in fig. 3.17 below	Geomorphological Practice	149 t fines, 47 t coarse,	Average per year

(In fact the Sear and Newson (1994) method is a pre-cursor to the to audit methods developed in this case study). Given that 93 cubic metres is a gross field observation of sediment-yield under a 22 cumec event, the method is probably very accurate at the level of a single event. However it predicts no yield below 10 cumecs, (as shown in Figure 3.16 above), and as such it doesn't consider the impact of lower flows when fine sediments are being delivered to the trap from the wider catchment. Therefore the method is not applicable to the derivation of an accurate yield over a maintenance timeframe of several years.

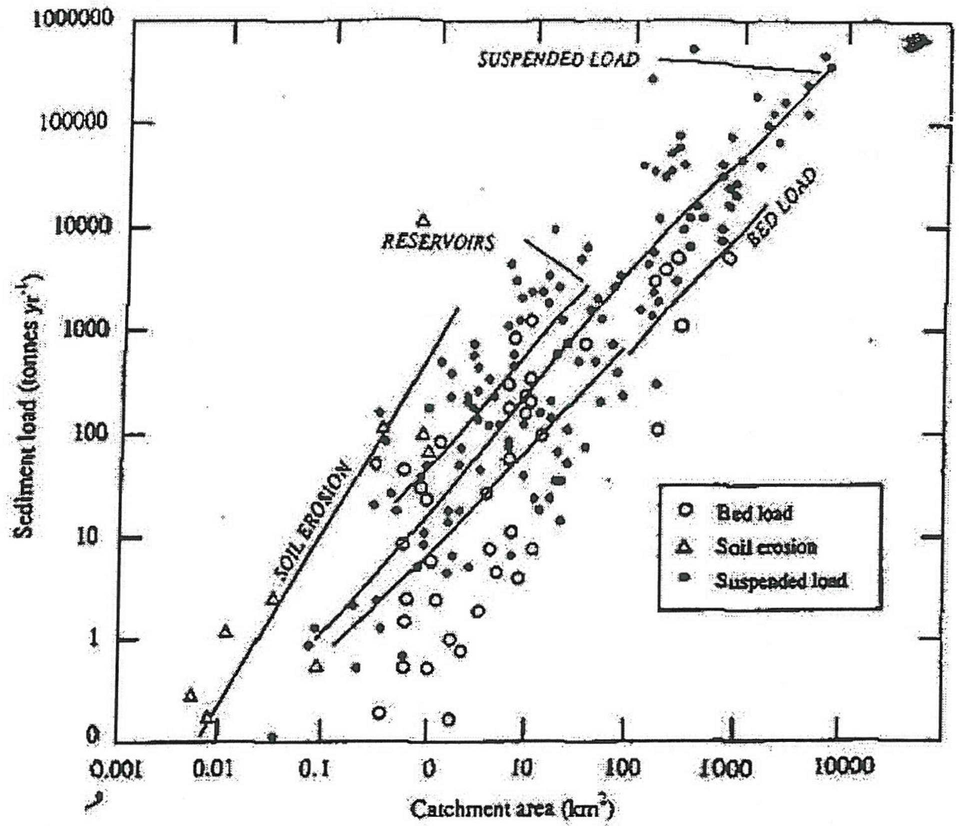


Figure 3-17: The Catchment Sediment-yield Method of Newson (1986)

The method of Newson (1986) produces a remarkably accurate yield estimate when compared to the field observations. As such there are no demonstrable advantages of using the audit techniques of this case study over the Newson method in this respect. However, the Newson method is simply designed to give sediment-yield information and the audit method is intended to provide much more information as will be discussed below. Also, Figure 3.17 shows the wide confidence limits of the regime approach.

In terms of producing usable information on sediment-yield, there is really no valid comparison between the audit methods developed in this case study and the various classifications and typologies discussed in Section 1.11.1. Such techniques are qualitative and they do not describe quantities of sediment supply or storage that could be used to derive estimates of sediment-yield. Such classification/ typology methods are more akin to the initial simple classification developed and rejected as not suited to flood defence application in the methods above.

Of the existing data collection practices described in Section 1.11.2, the standard catchment baseline audit has little actual quantification of the amounts of erosion and deposition that are occurring in the surveyed reaches, and the fluvial audit and detailed bank erosion assessment methods express such quantities in percentage terms as opposed to estimates of area and volume. However, all three of the methods could, with limited adjustments, be used to produce the same results as the audit methods developed in this case study. There are other areas of data needed that are not covered by these existing methods. The audit method developed here will move on to address these below.

An example of one such advantage that the audit method of this case study has over all of the existing methods of geomorphological practice is the ability to separate areas of sediment supply and storage which will occur under major flood events from sources and sinks that are active on a more frequent basis.

Figures 3.9, 3.10 and 3.13 show that, under the conditions of a major spate, not only are the quantities of net erosion and deposition substantially increased, but also the focus of supply shifts to an extended headwater zone. The middle reaches of the system then become an extended zone of net storage for the majority of the coarser fraction of sediments produced by these upland sources. The lower reaches continue to supply material, much of which will reach the area of the gravel trap. If the gravel trap were located between reaches 12 and 20, this information would be of major importance as the audit shows that the balance of supply and storage in these reaches shifts dramatically under conditions of a major spate event. However in the lower reaches there is not a major change in ratio of supply / storage under such conditions, (though quantities increase markedly). As such the audit method of this study allows answers to be given to two questions:

'Under an *extreme* flood event is there a possibility that coarse sediment mobilised in the upper reaches of the catchment may be transported to the lower reaches and the gravel trap site?'

'In similar circumstances does the ratio of sediment storage / output of the catchment system as a whole change from the proportions exhibited under more normal flow conditions, i.e. does sediment output increase exponentially?'

The comparison between the reach-by-reach sediment balances shown in detail in Figures 3.7 and 3.9 and the simple expression of this budget in Figure 3.12 strongly suggests that the zone of active sediment output is extended from the first kilometre of headwater channels to a 2.5 km. zone. However, this increase in sediment production is balanced by an increase in storage within the middle reaches of the catchment. Therefore the sediment balance in the 2-3km zone upstream of the gravel trap, although increasing locally, is not augmented hugely by a massive throughput of material from upstream.

In summary the audit method developed in this case study can be seen to have the following advantages over existing methods:

1. It produced more accurate estimates of yield than all engineering science methods considered.
2. It takes a fraction of the time to collect the field data required to give estimates compared to traditional methods of geomorphological science.
3. It is as accurate and applicable a method of deriving flood defence management information (such as predicted sediment-yields at a gravel trap location), as any existing method of geomorphological practice. While it is acknowledged that it does not necessarily show substantial benefits over some such methods, e.g. Newson (1986), Catchment Baseline Audit, Fluvial Audit, Detailed Bank Erosion Assessment, at least under normal sediment-transfer conditions, it can add an additional dimension of information in terms of predicting likely sediment-transfer behaviour under large flood conditions.

The audit methods will be developed in the second case study to address wider factors of flood defence application where such benefits may be shown.

The needs of the second global 'utility' objective of developing the audit, 'to identify what additional data are required to fulfil differing flood defence needs', particularly in relation to the gravel trap design have been discussed above. It has been shown that the audit method requires the use of a variety of simple hydraulic methods, which are readily available in reference texts, and also input from geomorphological studies in similar environments. Such additional data are required firstly to put estimates of erosion rates to observed erosion areas, and secondly to infer coarse sediment transport lengths in order to indicate supply zones from storage observations. The role of such data is to add information on sediment-transfer performance over time to the 'instantaneous' data of the audit observations. This is needed because the flood defence objective (gravel trap design) requires information on yield, and yield is a measure of accumulation over time.

In terms of the final *utility* objective of developing the audit, i.e. a demonstration of tangible benefits verses the costs, the following could be said. The trap cost £20,000 to construct. Considering that the audit takes approx. one hour per reach to perform (including particle size assessment), the audit of the 26 reaches of the Shelf Brook could be undertaken by a competent geomorphologist in 5 days (including walking time to access all reaches). A short report detailing the findings of the audit and extrapolating such findings to estimates of yield could then be prepared in 3 working days. This represents approx. £1500-2500 costs. Therefore it seems that this small relative cost represents a good investment to quantify the design and maintenance objectives.

3.8 Conclusions on the Application of the Audit Technique to the Shelf Brook

3.8.1 Summary of the performance of the audit with reference to the global project objectives

This case study has taken the first step in demonstrating the versatility of the audit method by successfully applying the method to a small, high-energy, upland catchment with a wide range of particle sizes involved in its sediment-transfer processes (sand – boulders), but with a coarse median bed-surface particle size (identifying it as a 'cobble-bed watercourse'). It has also initiated the testing of the versatility of the audit method as concerns flood defence application, in that it has demonstrated the applicability of the audit methods to the issue of 'controlling sediment transport with the use of a gravel trap'. At the same time it has indicated that the audit method may be used for post-project appraisal, offering a check on the design capacity of the trap and its proposed maintenance schedule. Additionally, it has shown that the method is applicable to the 'geomorphological role' of predicting sediment-yield with acceptable accuracy.

This study has also gone some way towards demonstrating the utility of the audit method, firstly by illustrating its advantages over existing geomorphological and engineering methods. Although, as discussed above, the comparison with methods of engineering practice is not applicable, there is clear evidence to suggest that the audit method produces results that are more accurate when (compared to field data) than traditional formulae based methods. It also has clear advantages over the traditional methods of geomorphological science, as there are massive time-savings as compared to the long-term collection of field data. In terms of the comparison with methods of geomorphological practice, the picture is perhaps a little more mixed. There are demonstrated advantages over many existing methods, in that the audit method will provide estimates of sediment-transfer over long periods of time (such as those required for flood defence maintenance application), as opposed to application purely to individual flood events, and it will also consider the role of fine sediments. However, there are four methods, (Newson 1986, the Catchment Baseline Audit, the Fluvial Audit and the Detailed Bank Assessment Method) which may either be capable of providing 'rapid appraisal methods' of sediment-transfer processes with similar accuracy to this audit method, in their current formats, or with only minor alterations. However, this method does have one advantage over all these four, in that it has the capacity to separate the field evidence of sediment-transfer that is currently occurring from that which may be attributable to major floods of the past. This is of particular importance in a small upland catchment where the significance of large, infrequent spate events on overall sediment-transfer activity is very great (i.e. the relative differences observed above in the proportions of sediment sources and sinks attributable to 'in-channel' and 'historical' sources).

The utility of the audit method has also been assessed in two further ways, in terms of the need for additional information. It has been shown that a variety of simple hydraulic methods and results from examples of geomorphological studies from similar environments, all readily available in the literature, are required in order to translate the 'instantaneous' observations of the audit into longer terms 'rates' of sediment-transfer. Finally the tangible benefits of the audit have also been addressed and the small cost of such a survey has been illustrated in comparison to the demonstrated value that the audit can add to a flood defence scheme.

A summary of the performance of the audit in this case study with reference to the global project objectives, (as defined in chapter 2), is given below in Table 3.11.

Table 3-11: Summary of Audit Performance in Shelf Brook Case Study

Global Objective	**Performance in the Shelf Brook Case Study**
Versatility – Application to:	
1. Different physical habitats	Yes – (High-energy, upland, coarse bed)
2. Different Catchment Sizes	Yes – (Small catchment)
3. Different Flood Defence management objectives	Yes – (Acceptable yield predictions in context of sediment trapping using a gravel trap)
4. Different Flood Defence project life-stages	Yes – (Post project appraisal)
Utility – Define:	
5. Advantages over existing methods	Yes – (with some specific provisos)
6. Additional data requirements	Yes – (In the context of this flood defence application)
7. Tangible benefits verses costs	Yes – (Low cost verses benefits)

3.8.2 Further research and methodological refinements required

The Shelf brook case study has established that the audit method developed is potentially a useful tool, however there are a number of areas of potential further investigation. Obviously the objectives of versatility defined by this project can not be fully investigated by the findings of a single case study. Therefore the second case study will seek to apply the revised audit methods not only to a different flood defence issue, but also to a catchment situation that is radically different to that of the Shelf Brook.

The areas of the audit and its application that require further development may be summarised as follows:

1. The audit should be applied to the watercourses of a full catchment system; as in the Shelf Brook case study it has only been applied to the main river stem, and the sediment-transfer role of the tributaries needs to be assessed more accurately. This will inevitably make the audit procedure a more time-consuming process.
2. Likewise the Shelf Brook is a predominantly unmodified channel system, and the audit methods should now be applied to a river catchment which contains a range of structures (bridges, weirs etc.) and channel engineering / modification (e.g. realignment, resectioning, reinforcement etc.).
3. The audit should also be applied at a wider scale in order to determine whether or not this produces clearer (larger) tangible benefits.
4. A lot of data that were collected in the audit process of this case study but were not directly used, therefore there is a need to review the data that are collected as part of the audit proforma.
5. There is a need to test the potential errors in field observations that can occur as part of this audit methodology. For example, observations of eroded and deposits areas are made by eye, and it is necessary to define the confidence interval of these estimates. In this study the quantity of field time required to undertake data collection was such that it was practical for one person to complete and analyse the work within the confines of a 'reasonable working timescale', (imposed by the requirements a typical Flood Alleviation Scheme).

Clearly, if the audit methodology that is being developed here is to be potentially applied to larger catchments then the issue of observer variability must be addressed. i.e. 'How consistent are the results of two individual observers assessing the same river reach and using the same audit proforma?'

6. Following on from the concept of consistency, a second question must be asked, that is one of repeatability: 'If the same observer were to assess the same river reach (under identical conditions) twice, would the results produced also be identical?'
7. The process of audit and assessment as developed in this case study provides a 'rapid appraisal' method of quantifying existing sediment-transfer characteristics, which can then be considered in relation to flood defence proposals. However, the audit methodology as it stands is not designed to address flood defence needs where there is a requirement to alter rates or characteristics of sediment-transfer. In order to develop and provide more in-depth practical information in this respect it is necessary to collect more detailed data on the types and causes of geomorphological processes, e.g. 'What type of erosion is occurring, is it mass-failure or gradual abrasion? What are the causes of that erosion, is it natural, or is it accelerated?' The inclusion of such observations would enable the production of tailored management suggestions, aimed not only at quantifying, but also at changing (managing) sediment-transfer processes.

3.9 Case Appendix 1: Field Data Collected For Comparison With Audit Methods

Data were collected using a variety of established 'geomorphological science' methods (as described in Section 1.9) for the purpose of comparing and assessing the findings of the audit methods developed in this case study. Such established methods included sediment-yield monitoring (repeat surveys at the gravel trap), the introduction and observation of painted tracers, and observations of erosion pins. Additionally, two hydrometric stations were established (the locations of the sites of these works are shown on Figure 3.2 above).

3.9.1 Methods

3.9.1.1 The introduction of tracers to measure sediment transport distances:

Sediment transport distances were assessed at the Shelf using yellow painted gravel and cobble particles as tracers, this technique uses the same simple methods as a number of works discussed above in Section 1.9.2, (e.g. Slaymaker, 1972; Ashworth, 1987; Komar and Carling, 1991). The tracers were introduced at the location marked on Figure 3.2 above. The site was selected as it was of typical slope, sinuosity and sediment size, it was more than a kilometre upstream of any atypical features that might affect natural patterns of sediment transport, (such as weirs, sluices or bridges), this distance exceeded the maximum reported transport distances in the tracer work reviewed in the literature, (as illustrated in Table 3.14 below). The site was reasonably accessible (the quantity of tracers removed, painted and returned to the Brook had a mass in excess of 250 kilograms). The particle size distribution of the bed surface was initially assessed using the Wolman (1954) technique. Table 3.12 below summarises the findings of the bed assessment, the number of tracers painted each textural class was then determined to represent the natural bed-size distribution. The quantity of pebbles (10-64mm) was however increased by 50% as they represent the smallest bed elements in the experiment and are thus hardest to relocate (as demonstrated in Butler, 1977). All tracers were measured (A, B and C-axis) using a micrometer and numbered. Sands and fine gravels were not included in the observations. The tracers were introduced on a riffle equally across the channel, within a one-metre band at the head of a relatively straight section of channel.

Table 3-12: Shelf Brook Bed Surface and Tracer Characteristics

Textural Class	Diameter (B-axis) Range (mm)	% Distribution in natural bed	Number of tracers	% Distribution in tracers
Pebble	10 – 64	33	99	42
Cobble (small)	64 – 130	43	86	37
Cobble (large)	130 – 206	16	32	14
Boulder	206 +	8	16	7
Totals	**10 – 760**	**100**	**233**	**100**

3.9.1.2 The monitoring of water levels and the establishment of a stage discharge relationship:

Two bankside stations were established continuously to record water levels in the Shelf Brook system; these were a short distance upstream of the gravel trap location, and upstream of the confluence of the Yellowslacks Brook with the Shelf Brook (shown on Figure 3.2 above). The positions were chosen to develop a flow record for the area of channel in which the tracers and erosion pins had been introduced, and for the trap area i.e. they were close enough to the tracers / pin and trap sites so that there were no significant tributary inputs. However, they offered a suitable gauging site (relatively straight channel, with a comparatively uniform profile), and were easily accessible for monthly data down-loading, while positioned in relatively vandal-proof locations. The stations were installed and rated according to the guidance given in British Standards Institution, (1980). The station records were used to derive flow records for the period Jan 1996 to May 1998. The record for the lower site is shown in Figure 3.18 below (in the form of monthly maxima). Although this period does contain a number of high flow records (including one significant flood-flow as discussed below), it should be noted that generally the period was very dry (the first 10 months for instance were officially designated drought months in NW England). This may mean that the results collected and presented below may be somewhat lower than observations that might have been collected in wetter years, and this is discussed further below.

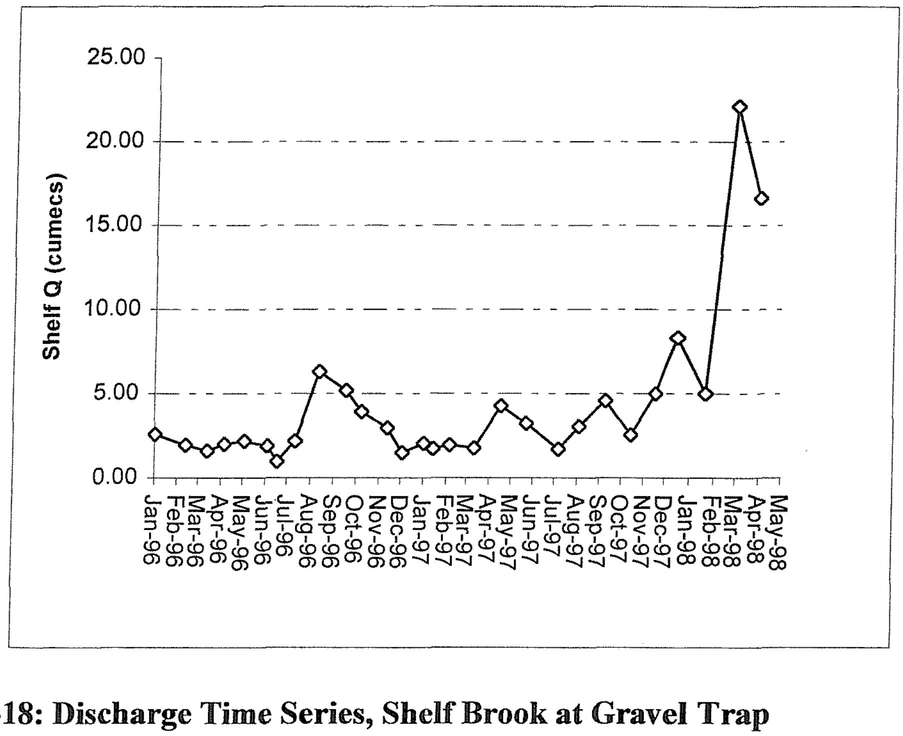


Figure 3-18: Discharge Time Series, Shelf Brook at Gravel Trap

3.9.1.3 Measuring sediment accumulation in the gravel trap:

This was undertaken using standard total station surveying techniques, such as those utilised in the work of Duck and McManus (1994), Walker (1995) and Milne and Sear (1997). The method collects a series of digital point data of x, y and z coordinates that represent the bed surface in the trap; the data are collected in the form longitude, latitude, and mAOD. This digital data were downloaded into ArcView Geographical Information System (GIS), and the Spatial Analyst routine was used to derive scale figures showing bed level across the trap,(an example of such a figure is shown below Figure 3.19). Subsequent surveys were used to quantify the accumulation of material in the trap; the results of these surveys are discussed in 3.9.2.2 below.

3.9.1.4 Measuring particle size of sediments accumulating in the trap:

The problems inherent in obtaining a representative measure of particle size have been investigated by several authors (Bray, 1972; Hey and Thorne 1983 and Church, Mclean and Wolcott 1987). Problems as concerns well graded riverine sediments (such as those found in the Shelf Brook) are 2-fold: firstly, particle size may vary in two directions, across the riverbed over relatively short distances, and vertically (particularly where the surface is coarser or 'armoured'). Secondly, in coarse bedded systems the inclusion of single large clast may bias a sample. Therefore a sample must be collected that is large enough to be representative of the wider bed, including the larger elements, and is also representative of the wider surface area of the bed and the full depth profile of the active bed (if required). During this period of initial observations only fine material was deposited (predominately sands), therefore it was possible to collect a representative sample by dividing the trap area into 20 sub-areas of equal size and removing a 50 gram sub-sample from each site, the total 2 kilo sample was then analysed under laboratory conditions according to the practices described in British Standard 1377. During subsequent sampling sessions the accumulation of coarser sediments in the trap meant that it was necessary to adopt a revised sampling strategy that combined this technique for fines with the grid sampling method of Wolman (1954). This composite approach is a simple version of the method suggested by Fripp and Diplas (1993) to cater for graded sediment sizes.

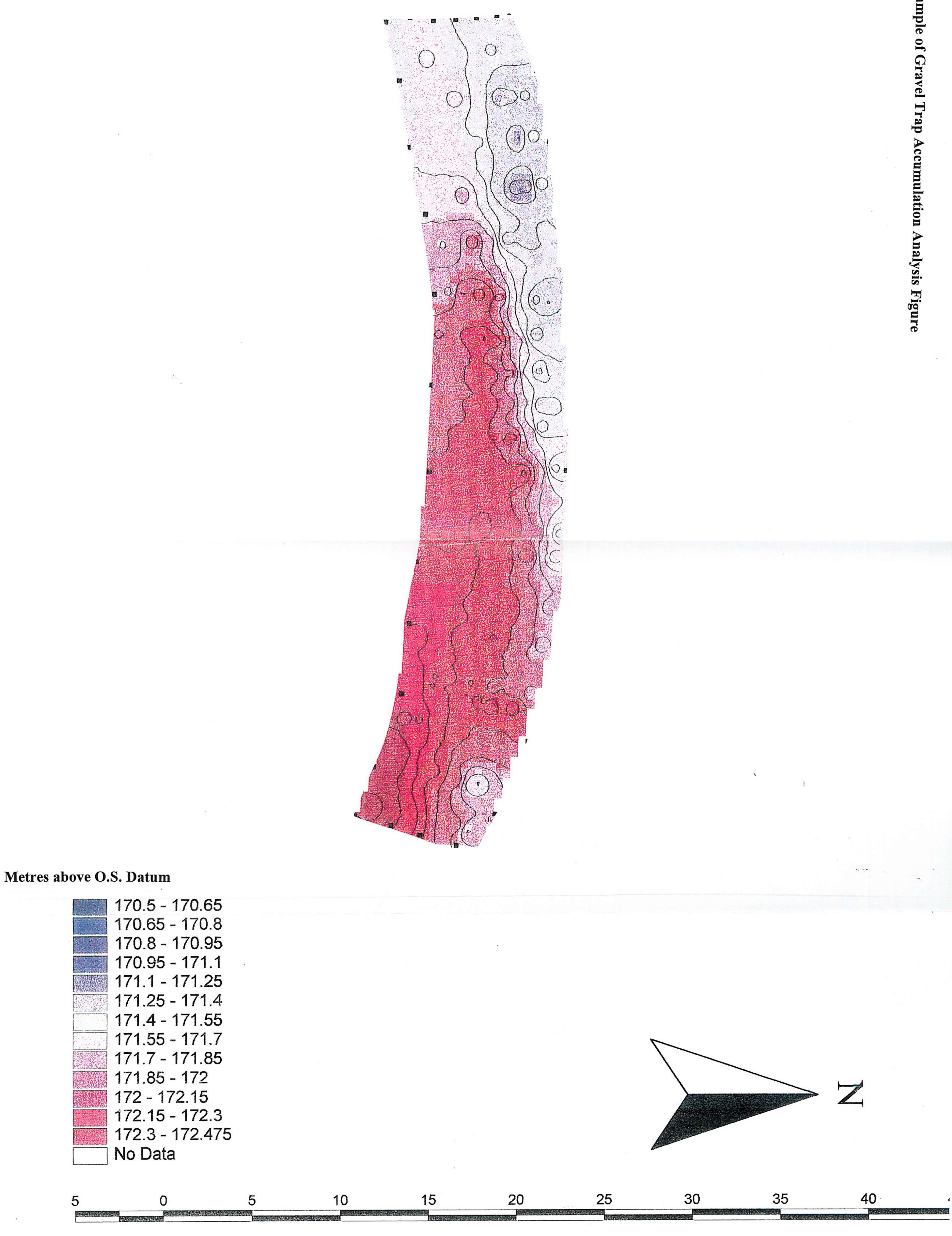


Figure 3-19: Example of Gravel Trap Accumulation Analysis Figure

i.e. The zones of coarse and fine deposition were initially identified and measured and the percentage surface area of the trap that each occupied identified. 100 b-axis clast measurements were then taken at random amongst the coarse sediments in the trap, while the zone of fine sediment deposition was sampled as before, the coarse and fine results were then combined and factored.

3.9.1.5 The introduction of erosion pins:

Erosion pins were introduced at the three sites show on Figure 3.2. The pins were half metre lengths of 5 mm steel rod, with yellow tape attached to their ends so as to aid relocation. They were hammered into the banks at the selected sites until they protruded 2cm from the bank surface. This work was done in July 1996 after rain (for ease of penetration). The pins were installed in vertical lines from the bank top to the low water level at 0.5 metre intervals. 120 pins were used in total. The three introduction sites were selected as, in the case of the tracer site selection, they were in areas where the Brook was of typical slope and sinuosity, with an absence of atypical features (including bank protection), and the sites were also relatively accessible. Additionally, they covered eroding cliffs from 10 to 200 square metres surface area, which were located on meander bends from 20 to 90 degrees, thus covering the majority of the range of variation for both these factors in the wider Shelf Brook system.

3.9.2 Findings

3.9.2.1 *Tracer observations:*

Table 3.13 and Figure 3.20 below shows a summary of the findings of the tracer work. In addition to the dates listed observations were made on the 3.1.1996 and 15.1.1997, however changes in location were not significantly different to the surveys of 17.2.1996 and 12.10.1996 respectively. Average and maximum distances moved are cumulative over the three recordings.

In general the recovery rates shown in Table 3.13 (49 – 61%) are good for this type of experiment. The 'loss' of tracers is primarily related to their burial during flow events, as the channel bed undergoes vertical movement of sediments as well as lateral (downstream) movement.

Table 3-13: Summary of Shelf Brook Tracer Observations

Date of survey	**17.2.1996**	**12.10.1996**	**5.4.1998**
Recovery Rate (%)			
Pebbles	55	48	32
Small Cobbles	72	71	63
Large Cobbles	78	65	65
Boulders	100	100	100
TOTAL	**61**	**56**	**49**
Mobile Fraction (of those recovered) (%) [i.e. the % of particles which had moved > 1 m.]			
Pebbles	30	56	60
Small Cobbles	31	44	52
Large Cobbles	20	33	36
Boulders	0	0	0
TOTAL	**28**	**47**	**49**
Average Distance Moved (of those recovered) (m.)			
Pebbles	0.3	4.0	19.6
Small Cobbles	0.3	3.4	19.0
Large Cobbles	0.3	2.2	11.7
Boulders	0	0	0.0
TOTAL	**0.3**	**3.4**	**16.7**
Maximum Distance Moved			
Pebbles	**2.9**	20.3	67.5
Small Cobbles	2.65	**21.5**	**124**
Large Cobbles	2.35	19.9	86
Boulders	0	0	0.5

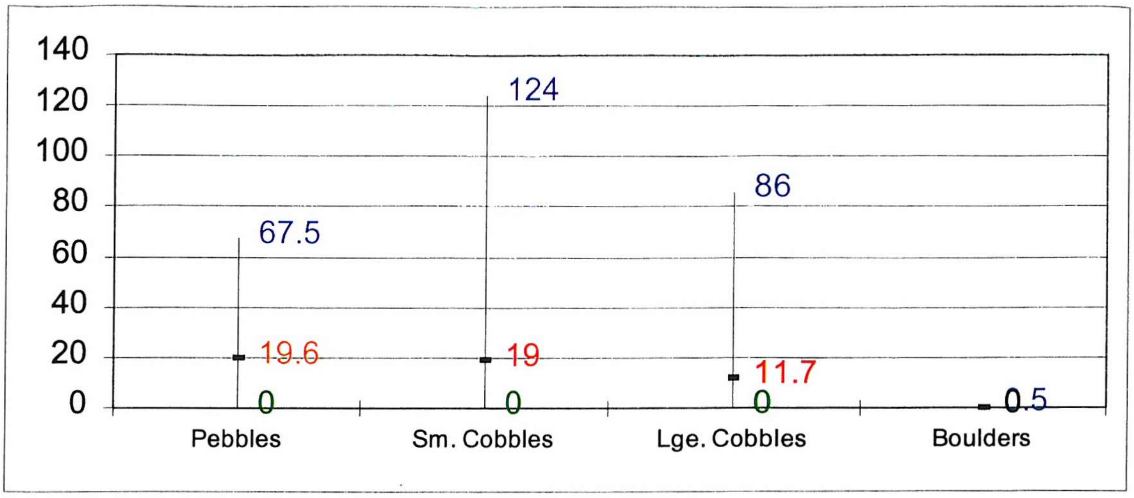


Figure 3-20: Minimum (green), Maximum (blue) and Mean (green) Travel Distances (m.) of Shelf Brook Tracers by Size Class

In all 3 observations made between February 1996 and April 1998, the data appears to show that smaller particles are more prone to burial. However, tracers may also have lost their paint due to abrasion or they may have been over-looked during re-survey, so while an indication of burial rate can be obtained by subtracting the recovery rate from 100, this is a 'non-conservative' estimate. The figures for recovery may be compared to the results of similar studies as summarised in Table 3.14 below. In the context of U.K. studies they may be seen as credible.

The average and maximum distances moved over time (full information shown in Table 3.13 above), clearly relate to the magnitude of the flow events that have occurred and specifically to the occurrence of the spate event of approx. 1 in 6 year return period on 6.3.1998, this will be developed in detail below. However the average distance travelled 16.7m., compares to other studies as follows. Not surprisingly they fall well below the international reference examples taken from the high mountains of North America and the European Alps, where the energy of river systems far exceeds those of this country. The distances are however similar to many of the studies from Britain.

Table 3-14: Examples of Results from Comparable Tracer Studies

Location and Stream	Grain Size (mm) Surface D_{50}	Tracers D_{50}	No. of Major Events[5]	Tracer Method	No. of Tracers	Recovery rate (%)	Distance Traveled (m): Average	Source
U.K. River Systems								
Carl Beck	50	15 - 130	2	Paint	279	98	1.14	Carling (1983)
Great Eggles-hope Beck	20	15 - 130	1	Paint	647	78	12.65	"
North Tyne	32 - 50	22 - 125	3	Paint	700	38 - 60	5.5 - 10.1	Sear (1996)
Severn	35 - 38	Gravel	3		250	40 - 79	11.7 - 23.0	Thorne (unpubl.)
Irwell	40	5 - 160	1	Paint	160	22.5	11.9	Birch (1999)
Allt Duhaig	51 - 62	41 - 147	4	Paint	734	69 - 76	7.3 - 16.7	Ashworth (1987)
North America								
R. Carmel, Calif.		55-130	10	Lithology	>500		700	Kondolf & Matt-hews (1986)
Rio Grande, New Mexico	21-33		1	Magnet	2000	High	188	Leopold and Emmett (1983)
Horse Creek, Wyom.	40	32-127	1	Alum-inum Tagged	159	35	84	Butler (1977)
Carnation Creek, Canada		16-180		Magnet	183	80	52.6	Hassan and Church (1992)
Harris Creek, Canada	60	6-512		Magnet & Litho-logy	Approx. 250	75	92.9	"
Seale's Brook, Canada	91	6-250		Paint	242	5	86.5	Laronne (1973)
European Alps and Environs								
Virginio Stream Italy	40	18-130	4	Paint	3935	22	223	Tacconi et al. (1990)
Lainbach Baveria	64	85-130	1	Radio Trans-mittor	5	100	470	Ergen-zingeret al. (1989)
Lainbach Baveria	100	30-170	19	Magnet	>2000	23-100	8 – 317 (different events)	Gintz et al. (1996)

Of the British examples from Table 3.14, of particular interest is the comparison with the work of Carling (1983) at Great Eggleshope eck, North Pennines, where average transport distances were recorded as 12.65m compared with 16.7m in this study. Only 1 'flood-flow' of bankful or greater occurred during the observation period, as is the case for this study (as shown in Figure 3.18 and Table 3.3 above), and it was of comparable magnitude. The catchments are also of a similar size, 11.7 and 14.9 sq. km., while the Eggleshope Beck is slightly steeper and less sinuous with a finer average bed material size. The maximum transport length in Carling's work was less than that of this study (63m. versus 124m.) and the assumed burial rate was also less (22% verses 51%). However, the similarities between the catchment sizes, locations, elevations and flow characteristics mean that if estimates of sediment transport under normal to bankful flow conditions were required in the future for an un-monitored upland catchment in North West England, then the results of the work of Carling and this study might be used to derived working ranges for transport statistics.

It is also worth highlighting a comparison with the work of Birch (1999) on the River Irwell, as this study site is within the Mersey basin, (as is the Shelf Brook), and the period of observation covers the same period as this work, including a flood event of 6.3.1998. Similar average transport distances of 11.9m were recorded on the Irwell in the aftermath of this event, although recovery rates and maximum transport distances were lower. This may be attributable respectively to the unconsolidated nature of the bed surface, and the potentially lower stream power at the Irwell site.

In all three observations recorded on the Shelf, particle size appears to affect the percentage of recovered particles that moved, with a consistently higher fraction of smaller particles moving. Also there is a general trend for smaller particles to move further. The concept that maximum transport distance, at least, may be linked in some way to increasing particle dimensions or mass has been demonstrated by Hassan and Church (1992), providing the tracers used represent the full particle size range of the gravel/cobble elements of the natural bed. This pattern is logical, however the many variations in the hydraulic processes governing sediment transport, combined with the intricacies of the interactions between sediment particles, means that such patterns are

---

5 Defined as Mean Annual Flood or Greater.

frequently blurred in sediment transport studies. Figure 3.21 supports this theory by suggesting a relationship, much the same as Hassan and Church's (1992), for approximate maximum transport distances based on the dimensionless particle size, (b-axis / median b-axis), and dimensionless distance travelled, (distance travelled / average distance travelled).

3.9.2.2 *Accumulation monitoring at the gravel trap:*

In March 1996 an initial assessment of trapped sediments was undertaken. It was found that over the preceding 6 month period the majority of the 95 tonnes of material accumulating in the gravel trap was sand, median diameter 18mm (see Table 3.15 below and Figure 3.22).

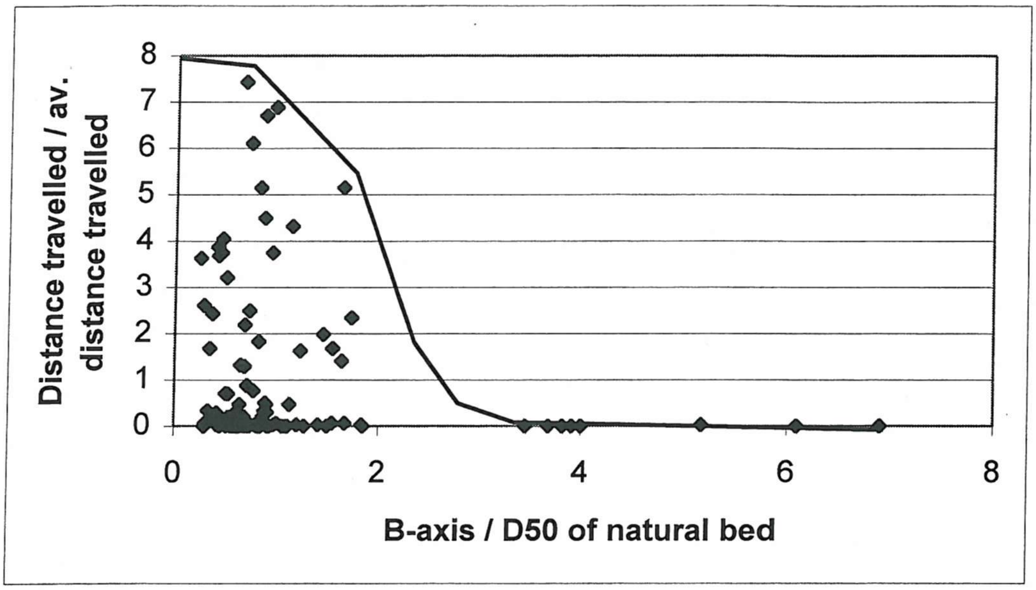


Figure 3-21: Relationship Between Dimensionless Transport Distance and Particle Size of Shelf Brook Tracers

The flows during this period were relatively low (see Figure 3.18). Very little coarse sediment movement was observed during this period, (see Table 3.13). The gravel trap was observed to be trapping even the finest sands, the quantity of material trapped, in conjunction with the observation that virtually no gravel transport was occurring, implied that the trap was effectively retaining the total sediment load of the Shelf system. At this point in time the trap had filled to approximately one-third capacity. As sand-sized particles may travel for greater distances than gravels under the same flow condition, it became evident that the supply reach defined by Sear and Newson (1994) must be revised. In other words the coverage of the audit developed in this case study should be undertaken on a catchment-wide basis to include sources of fine sediments absent from the previous study.

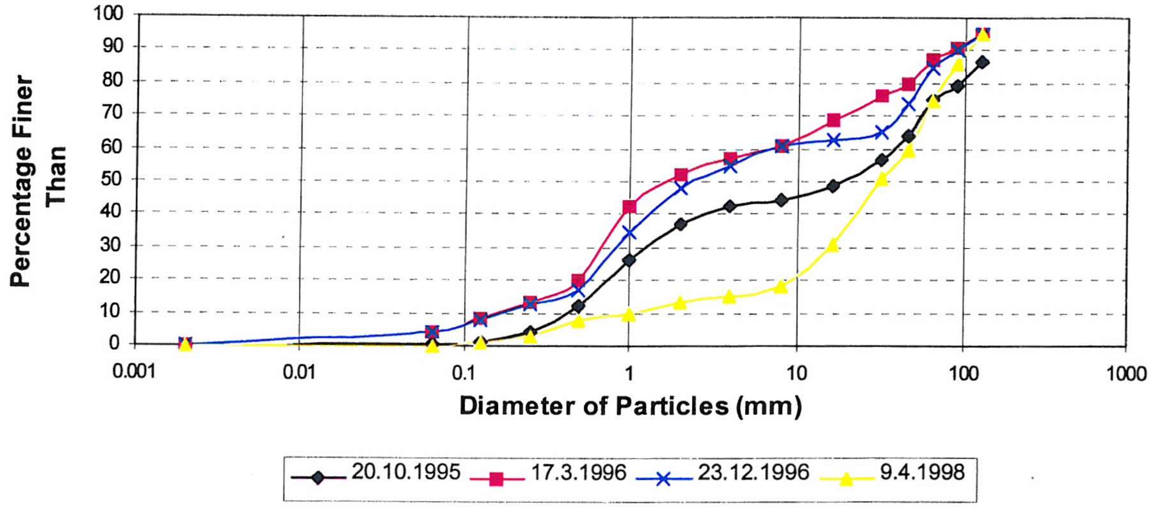


Figure 3-22: Particle Size Analysis Results of Shelf Brook Gravel Trap Sediments

Table 3-15: Summary of Sediment Retention in the Shelf Brook Gravel Trap

Survey Date	**Change in mass of sediment retained in trap from previous survey (tonnes)**	**Sediment texture (mm)**			**Max. observed Q since previous survey (cumecs)**	**General Comments**
		D16	**D50**	**D84**		
20.10.1995	0	0.85	18	100	N/A	Soon after construction trap virtually empty.
17.03.1996	95	0.35	1.05	54	1.55	Steady accumulation of fine sediment.
23.12.1996	-10	0.5	1.75	62	6.3	Moderate spate event flushed some sand and deposited small quantity of coarser material.
09.04.1998	247	9	30	87	22	Aftermath of flood event of 6.3.1998.

As discussed above and shown in Table 3.15, over the initial 6 months of observations sediment retention in the trap commences with a steady accumulation of fine material (95 tonnes) from the initial survey of 20.10.1995 to 17.3.1996. Particle size analysis of the sediment retained in the trap during this period shows that the average (D_{50} or median) size of material was 1.05mm (coarse sand), the D_{16} (16^{th} percentile) and D_{84} (84^{h} percentile) show that there were also fine sands and small gravels present. A small spate event then occurred on the 24.8.1996 of 6.3 cumecs, (approx. 45% of the mean annual flood), this appears to have flushed some of the fine deposits from the trap, and deposited a small quantity of coarser elements at the head of the trap). This is reflected in the relative change in the quantity of sediment contained in the trap at the survey of 23.12.1996 (minus 10 tonnes). It is also shown in the change in particle size characteristics shown in the increase in coarseness of the D_{84}. The effects of a major spate event of 22 cumecs, (6.3.1998, estimated at 1 in 6 year return period), are then noted in the last survey when an increase of 247 tonnes is recorded. This material is shown to be relatively coarse, (as shown by figures for this date in Table 3.15 and in Figure 3.21). A full flow record for this period (monthly maxima) is shown in Figure 3.18.

The total estimated accumulation in the gravel trap over the 2.5 years of post-construction observation of 332 tonnes (95 – 10 + 247, see Table 3.15), equates to an average catchment output of 8.9 $t.^{-1}$ $km.^{-2}$ $yr.^{-1}$ When compared with international examples of sediment-yields (table 3.16) this rate equates to the less active catchment outputs. However, the overseas examples included in this table are predominately from high mountain, high-energy river systems, and are included solely to provide an indication of the approximate global range of sediment-yields from upland catchments. Therefore this relative position is not surprising.

Table 3-16: Examples of Results from Comparable Sediment-yield Studies

Researcher / Team, Year	Location	Method	Catchment Area (Km^2)	Texture (D_{50}mm)	Dura-tion of Rec-ord (Yr.)	Catch-ment Yield $t.^{-1}$ $km.^{-2}$ $yr.^{-1}$)
European Alps and Environs						
Warburton 1990	Output of Bas Glacier d'Arolla, Switzerland	Topo-graphical Survey and Helly-Smith	7.6 (Glacial)	Gravel / Cobble	1	2870 NB. (Immed. Pro-glacial)
Bezinge, Clark, Gurnell and Warburton 1989	Grande Dixence, Switzerland	Trap	116.5	Gravel	11	27.9-51.3
Becht 1994	Kesselbach Switzerland	Trap (Tyro-lean Weir)	38.5	Gravel	3	28
International Rheinregu-lierung 1990	Rhine at Lake Constance, Switzerland	Lake Survey	6123	Gravel (30-40)	23	17.31
North America						
Martin and Church 1995	R.Vedder, Brit. Columbia, Canada	Topo-graphical Survey	1230	Gravel (20-30)	9	11.7
Kondolf and Matthews 1986	R.Carmel, Califonia, U.S.	Helly-Smith	660	Gravel	2.25	9.4
Adenlof and Wohl 1994	East St. Louis Creek, Colarado, U.S. Rockies	Helley-Smith	8	Gravel (40)	1	6
Ashmore and Church 1995	R.Fraser, Brit. Columbia, Canada	Topo-graphical Survey	230 000	Fine Gravel	17	0.93-1.14
Britain						
Duck and McManus 1994 (1)	Pinmacher, Ayr, Scotland	Reservoir Survey	0.4	Gravel	85	22.35
Duck and McManus 1994 (2)	Holl, Fife, Scotland	Reservoir Survey	4	Gravel	86	9.45
Moore and Newson 1986 (1)	Tanllwth, Seven, Mid. Wales	Trap	0.9	Gravel	10	38.4
Moore and Newson 1986 (2)	Cyff, Wye, Mid. Wales	Trap	3.1	Gravel	10	6.4
Stott Ferguson Johnson and Newson 1986	Monachyle, Balquhidder, Scotland	Check Dam Trap	7.7	Gravel / Cobble (64)	3	0.12
Stott Ferguson Johnson and Newson 1986	Kirkton, Balquhidder, Scotland	Check Dam Trap	6.9	Gravel / Cobble (64)	3	2.09

Table 3-17: Examples of Yields from Other Upland Gravel Trap Sites in North West England and Wales

Site	Catchment Area	Average Yield (T/sq.km./yr)	Source
Applethwaites	1.31	46.1	Sear and Newson (1994)
Beckthornes	0.51	91.6	Sear and Newson (1994)
Fornside	0.43	184.7	Sear and Newson (1994)
Langthwaite	4.50	734	Sear and Newson (1994)
High Nook	2.21	108.4	Sear and Newson (1994)
Kiln Howe	0.84	268.3	Sear and Newson (1994)
Mines	0.94	369.0	Sear and Newson (1994)
Doddick	0.91	667.7	Sear and Newson (1994)
Coalbeck	5.83	17.8	Sear and Newson (1994)
Coledale	6	57.7	Sear and Newson (1994)
Embleton	4.64	73.7	Sear and Newson (1994)
Afon Gele	17.8	100	Personal Communications[6]
Nant Barrog	4.25	300	Personal Communications[5]

Of more direct significance is the comparison between the yield for the Shelf Brook and the British examples in Table 3.16, where the recorded yield appears to relate closely to many of the figures from similar upland catchments, (e.g. Duck and McManus 1994 [2] and Moore and Newson 1986 [2]). However, perhaps the best direct form of comparison is to examine the results of Table 3.17. From this examination it appears that the yields at the Shelf Trap are comparatively very low, i.e. lower than all the observations recorded. However, it is important to note two significant points.

Firstly, the design of the Shelf Brook trap is deliberately 'leaky'; in other words the arrangement of the individual boulders, which form the lodge at the downstream end of the trap, is such that it allows the passage of fine sediments under spate flows. The trap did not operate in this way during the initial months of this project due to low flows, and this led to the assumption of total-load trapping, however subsequent resurveys showed that under higher flows the trap retained mostly gravel and cobbles, letting the

6 Personal Communications between: Phil Weaver (NRA, Welsh Region) and David Sear (University of Southampton), 24.2.1994, and Jim Walker (Environment Agency, NW Region) and Phil Weaver (Environment Agency, Welsh Region), 25.3.1999.

finer particles escape. Therefore the final figure of accumulation in the trap is not an accurate figure of total catchment sediment-yield.

Secondly, the size of the catchments on which the traps in Table 3.17 are located should be noted. All of them, with the exception of Afon Gele, are substantially smaller than the Shelf. Sear and Newson (1994) propose an inverse relation between catchment size and yield per sq. km., however this alone is probably not sufficient to account for the comparative lack of yield in a catchment such as the Shelf, where it has been demonstrated (through the tracer work above) that sediment movement is not untypical of an upland catchment in NW England. The size of the majority of catchments in Table 3.17 means that in most cases the coarse sediment 'supply reach' for the trap will include virtually all of the catchment area. In the case of the Shelf, the tracer work (discussed above) clearly illustrates that this is not the case and that even under a moderate spate event of approx. 1 in 6 year return period, the 'supply reach' is at most a few hundred meters of channel upstream of the trap, which has a local drainage area of no more than 1 sq. km.

If one first makes two observations above that: 1. the trap only sporadically traps fine sediments (travelling to it in suspension), as it leaks fines under spate, and 2. the sediment supply zone for coarser, bedload material is local, and one then compares the particle size of the sediments found in the trap with that of a natural section of channel immediately upstream (containing no bars or other deposits), it is possible to make assumptions about the operation of the trap over time. In other words it is possible to separate the trap's capacity to retain fine sediment (travelling largely as suspended load) from a wider catchment supply zone, and coarse sediment (travelling as bedload from a local supply zone), and to use this distinction to develop a more reasonable figure for trap yield in tonnes / sq.km./ yr:

One may deduct 77 tonnes as estimated suspended load (from a catchment wide source) from the yield of the final observation at the trap, (as shown in Figure 3.23). The figure deducted is derived by comparing the particle size distribution of sediments in the trap with the particle size distribution of the substrate immediately upstream of the trap (sampled in 1995 at the beginning of the operation of the trap). As can be clearly seen in Figure. 3.24, particles finer than 31.5mm are extremely uncommon in the surface composition of the natural bed and are thus discounted. [This removes the fine particles which were only deposited as the geometry of the trap led them to drop from suspension]. One is then left with a yield of 170 tonnes of material over 2.5 years from an estimated 1 sq.km. of 'active catchment supply zone' or 68 $t.^{-1}$ $km.^{-2}$ $yr.^{-1}$. This yield compares much more directly with the less-active traps in Table 3.17. It also compares well with the Afon Gele trap, which has a similar catchment size and where a similar supply regime is thought to be in operation.

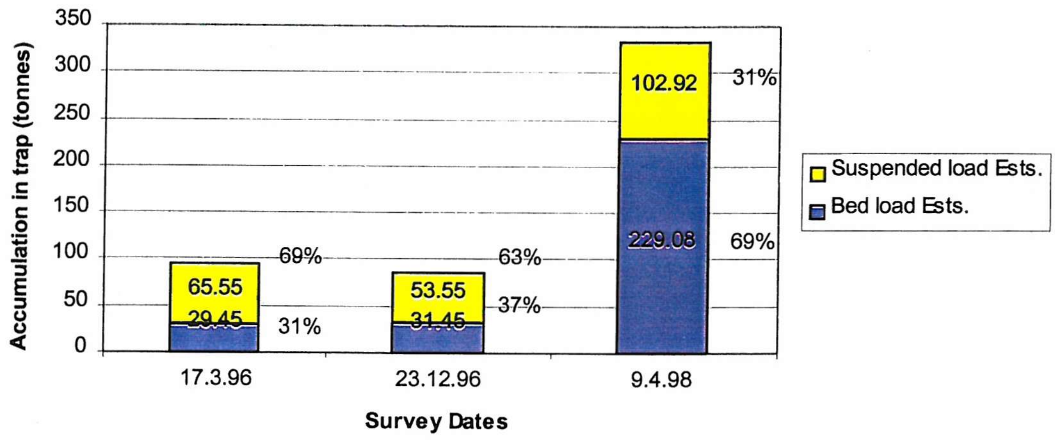


Figure 3-23: Estimates of Bedload and Suspended Load in the Shelf Brook Gravel Trap

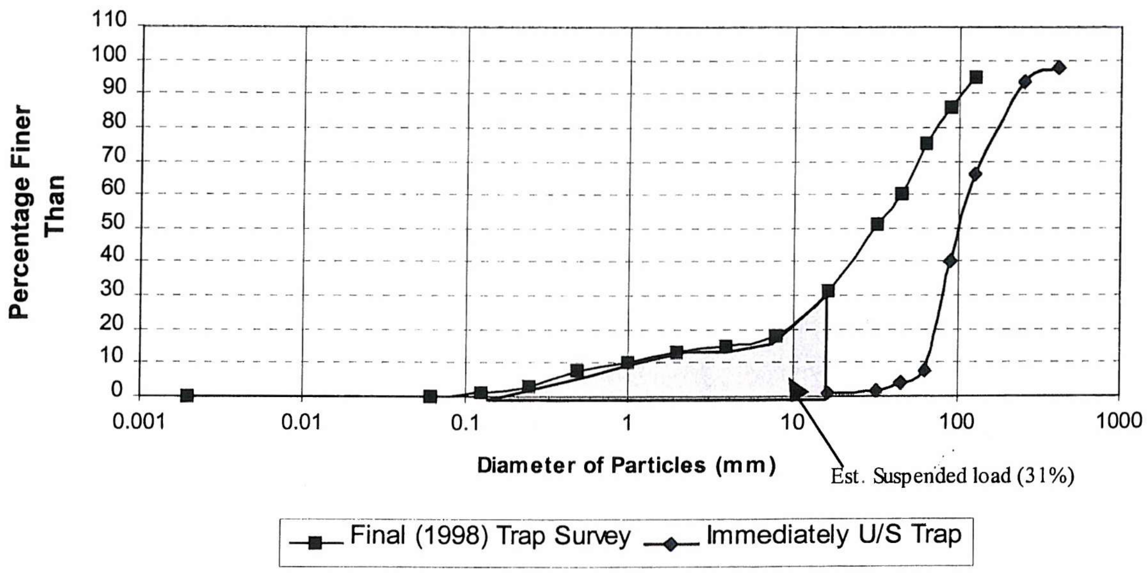


Figure 3-24: Particle Size Analysis of Final Gravel Trap Observations Compared to Particle Size Analysis of Area Immediately Upstream of Trap

3.9.2.3 Erosion pins:

The erosion pin work in the catchment makes it possible to tentatively extrapolate from the figures of active in-channel bank erosion given in Figure 3.8 above and to estimate eroded volumes. The total area of in-channel erosion in the catchment is 1860 square metres. Observations made in July 1997 (one year after introduction) showed that, given an average observed rate of bank retreat of 100mm./yr., (min. observed rate 35mm, maximum 175mm), the catchment produces approx. 190 cubic metres of sediment per year. The total quantity of in-channel deposits in the catchment is approx. 1450 cubic metres; and this suggests that under bankful and moderate spate sediment transport conditions the catchment is in a state of overall net sediment storage. The ratio of historic *and* in-channel erosion to deposition is approx. 9500 square metres to 14100 cubic metres. This suggests a much higher net rate of erosion, however the erosion pin work is not extensive enough to suggest a volume for erosion under major spate events. It is not justifiable to compare this figure of 190 cubic metres / yr. to the recorded accumulation in the gravel trap (93 cubic metres over 2.5.years) in an endeavour to develop a sediment delivery ratio for the catchment, as the trap is leaky and its coarse sediment supply zone is local as described above.

3.9.2.4 Conclusions on sediment transport in the Shelf Brook catchment, and yield at the Shelf Brook gravel trap

The observations of accumulation in the trap over the 2.5-year observation period imply that the trap has three discrete 'phases' of operation, which are attributable to different flows.

- *Phase 1* – Low to moderate flows (maximum observed flow less than approx. 3 cumecs), trap has very high efficiency, retaining most of the sediment load. However the majority of the sediment load under such flow conditions comprises sands and fine gravels.
- *Phase 2* – Under moderately high flows a critical threshold for fine sediment transport is reached. The trap is no longer capable of retaining incoming fine sediments, indeed the hydraulic properties of the trap (relatively straight with smooth concrete walls), means that it forms a more efficient area of fine sediment transport than the natural channel upstream of it. Therefore, under such conditions

some fine sediments are flushed from the trap. A small quantity of gravels and small cobbles are also transported into the trap under such flows, and these are retained; however the net effect is one of loss.

- *Phase 3* – At spate flows (in excess of the mean annual flood), wholesale coarse sediment transport begins in the Shelf Brook. As in phase 2, the majority of finer material passes through the trap, but substantial quantities of gravel and cobbles are retained.

The tracer work over the same period also implies that the sediment-transfer characteristics of the wider catchment also conform to this '3-phase model'.

- *Phase 1* – Little pebble and cobble movement occurs, what does is transported over extremely short distances. (However, evidence from the gravel trap indicates that fine gravel and sand is however transported throughout this period).
- *Phase 2* - More pebble / cobble movement occurs; however transport distance is still largely restricted to a few metres maximum.
- *Phase 3* – Wide-scale bed surface movement occurs and pebble/cobble transport occurs, in some cases in excess of 100 meters.

These 3 phases correspond approximately to the sediment-transfer conditions as described by Carling (1983) as 'winnowing' conditions (phase 1) and 'scouring' conditions (phase 3), with phase 2 presenting something of a threshold state.

3.10 Case Appendix 2: Formulae Used In The Estimates Of Sediment-yield At The Gravel Trap

BAGNOLD (1966) SEDIMENT TRANSPORT FORMULA (EXCESS STREAM POWER). [Adapted from Sear and Newson 1994].

Entrainment commences when: w >= wo

I.e. calculated stream power (w) [$watts^{-1}$ m^{-2}] exceeds a critical threshold (wo) [dimensionless]

Total bedload movement is calculated as follows:

$$\mathbf{ib = 0.1[((w-wo)/0.5)^{1.5} (d/0.1)^{-2/3} (D_{50}/0.0011)^{-0.5}]}$$

When: w=pgQS/b and $wo = 290(D_{50})^{1.5\log}(12/d/ D_{50})$

Where:

D_{50} = mean particle diameter (intermediate axis) [m]

Q = discharge [m^{-3} s^{-1}]

S = slope [m/m]

p = density of water [kg^{-1} m^{-2}]

g = gravitational acceleration [m^{-1} s^{-2}]

d = depth at bankful [m]

b = stream width [m]

MODIFIED SCHOKLITSCH FORMULA , BATHURST, GRAF AND CAO (1987). [Adapted from Sear and Newson 1994].

The onset of sediment transport occurs when the critical unit water discharge is met:

$qc = 0.21\ g^{0.5}D16^{0.66}S^{-1.12}$

Bedload transport rate is then obtained by:

$\mathbf{ib = 0.4S^{0.66}(q-qc)^4}$ (where q-qc <1)

$\mathbf{ib = 0.4S^{0.66} (q-qc)}$ (where q-qc >1)

Where:

ib = bedload transport

S = slope (m/m)

g = gravitational acceleration [m^{-1} s^{-2}]

D_{16} = diameter of sediment size at the 16^{th} percentile(mm)

Q = discharge (cumecs)

W = channel width

Q = unit water discharge (Q/w)

Qc = critical unit water discharge

MEYER PETER FORMULA (1934).

$$\mathbf{ib = [250q^{1.66}S\text{-}42.5D]^{1.66}}$$

Where:

ib = sediment transport

q = discharge (cumecs)

S = Slope (m/m)

D = Particle size (mm)

Chaper 4: Case Study 2: River Mersey Flood Alleviation Scheme (Application To The Upper Mersey Catchment)

4.1 Flood Defence Scheme Background and Sediment Issues

4.1.1 The Mersey and flood defence in south Manchester

The Mersey Flood Alleviation scheme covers a river length of approximately 20 km, flowing through the south Manchester conurbation extending from Stockport town centre (railway viaduct marks upstream extent of the scheme) to Stretford, (M60 Carrington spur road bridge marks downstream extent of the scheme), henceforth this river length will be referred to as the focus reach, (see Figure 4.1). This area includes the residential areas of Stockport, Cheadle, Gatley, Didsbury, Northenden, Chorlton, Sale and Stetford, and the flood storage basins of Didsbury and Sale Ees.

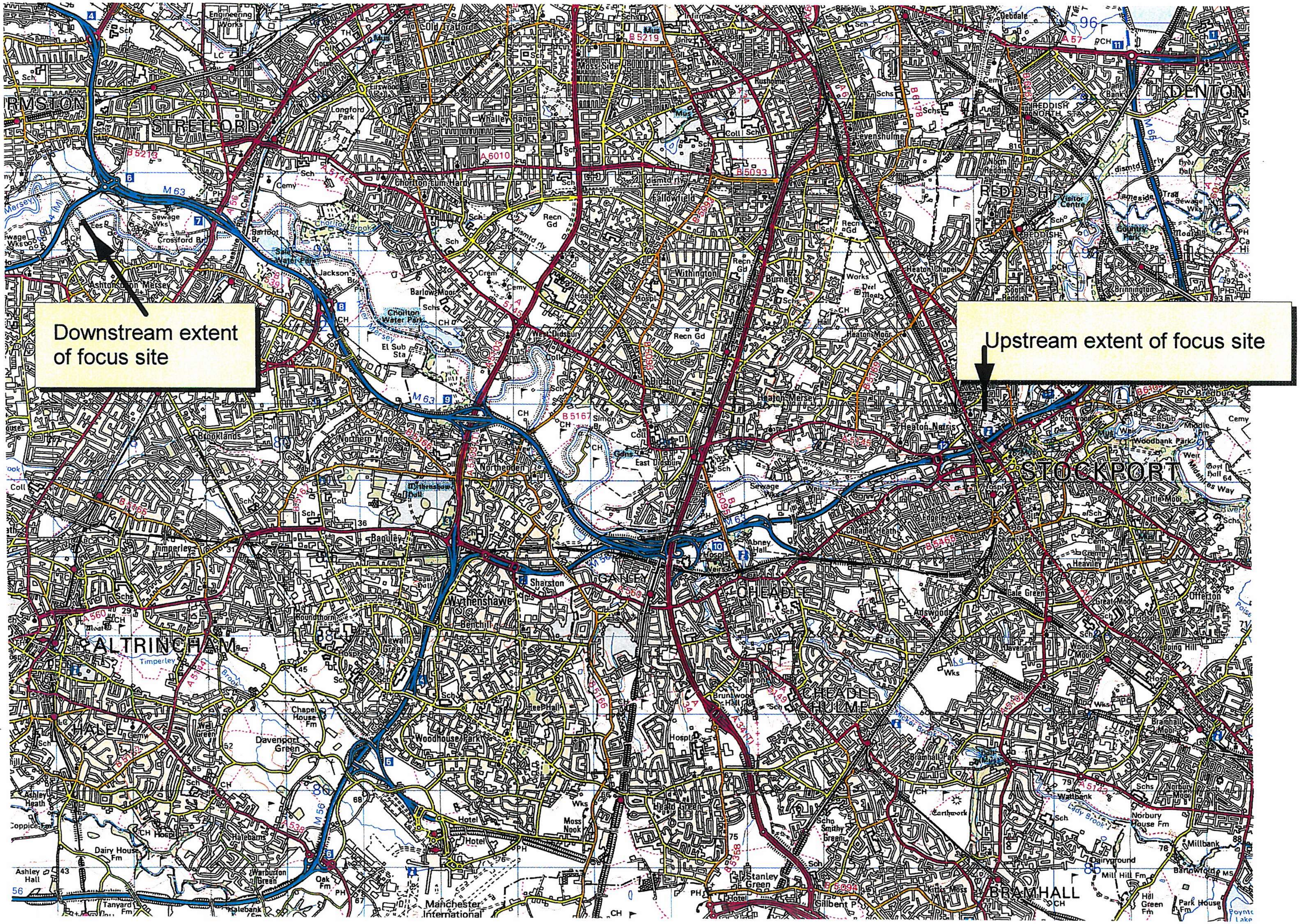
Channel and channel-associated works of one form or another have been undertaken in this area on an ad-hoc basis for at least the last two thousand years, (North West Water, 1976). Such works have primarily concentrated upon the construction of bridges to carry a number of important trade routes across the river (which is large enough to render it unfordable at all but very low flows thorough the length of the focus area), an example of one such ancient route is the modern day A6 that is of Roman origin. However, there has also been a long history of raising flood embankments along the course of the Mersey to protect settlements and agricultural land from flooding, through such developments have not been without controversy. For example, circa 1800 a flood caused damage to the newly constructed Bridgewater Canal aquaduct which crosses the Mersey at Sale and the canal trustees sued the landowner upstream on the grounds that 'in raising flood embankments they had prevented the water from having a free course, which had concentrated the river, adversely impacting upon their aquaduct', (Scott Wilson Kirkpatrick & Co., 1999a). From the Victorian period onwards, in central Stockport at least, the practice of developing right up to the bank crest in places and walling the river channel was common. In the early 1960's a comprehensive programme of resectioning and embankment works was undertaken by the Mersey and Weaver Rivers Board (a forerunner of the Environment Agency) in order to join, rationalise and improve the defences along the banks of the Mersey in the focus reach.

The current scheme seeks to review all these existing defences and the levels of flood protection that they offer, suggesting improvements where necessary to raise the level of protection to 1 in 100 years for most urban areas within the floodplain, and assessing the need for the repair, upgrading or replacement of existing structures (such as embankments, walls, weirs etc.). The scheme also seeks to review the flood defence maintenance requirements of the focus reach, and to produce a new 'maintenance management plan'. This plan will deal largely with sediment related issues (as discussed below). The length of the focus area and the shear volume / coverage of the Mersey in spate, (as indicated in Table 4.4), means that this is a large flood defence scheme in excess of £10 million. This includes all capital works and maintenance works over the 100 year design life of the scheme. The scheme was at feasibility phase for the duration of the geomorphological contribution described below until the publication of the project initiation document in August 1999, (Scott Wilson Kirkpatrick & Co., 1999b) marking the transition of the scheme to the 'construction' phase.

4.1.2 Definition of the flood defence sediment problem

The channel throughout the majority of the Flood Defence focus site is heavily modified. During the late 1960's it was realigned, resectioned, widened and embanked, producing a near constant trapezoidal channel form that is of greater than natural capacity. This has produced an environment of extremely low geomorphological diversity; with a largely planar silty bed, low numbers of bedforms & flow features, regular bank angles and heights, moderated slopes, a few bar features.

Figure 4.1 Location of Mersey Flood Alleviation Scheme Focus Site O.S. Landranger 109 1:50,000



The channel in the Flood Defence focus area is also prone to extensive fine sediment deposition. This is attributable to a number of factors, including sediment supply characteristics, partly the result of the natural catchment properties. The Shelf Brook case study presented above, for example, illustrates that sediment is produced in large quantities by the upland headwaters of the catchment. Fine sediments are delivered swiftly to the Manchester area though the upper and middle reaches of the catchment. The historical operation of these natural processes is well documented; accounts of the 1700's state that the silt loads carried by the Mersey acted to enrich the floodplain fields which they regularly inundated, (North West Water, 1976). However, these naturally high levels of sediment production have almost certainly been increased as a product of urban expansion and changes in land management practice. Such practices may include changes in stock management, in particular increased grazing pressures, patterns of forestry management and methods of tillage and arable farming. Butcher et al. (1992), in work undertaken for Yorkshire Water, demonstrate that land management changes were in part responsible for changing sediment-yields in reservoirs observed on the eastern side of the southern Pennines. None of the sites investigated were in the Upper Mersey catchment, however many were only a short distance east across the watershed, and it seems reasonable to conclude that similar patterns of process change have occurred in the catchment of this case study.

In addition to factors of sediment supply, the fine sediment deposition problem is also attributable to channel form at the Flood Defence focus site. Historically the channel was prone to active bed erosion; bed lowering as great as 1.8m was recorded between 1932 and 1947, (North West Water, 1976). Indeed, given natural or semi-natural river form at the focus site, the river would probably vary between long term patterns of erosion and deposition, which would shift reflecting changes in the sediment supply and the continuity of sediment transport in the upper catchment. However, major channel alterations in the 1960s (described above) have changed the geomorphological nature of the channel, producing a predominantly depositional environment. This work was undertaken to accommodate in-bank flows in excess of 250 cumecs; it has produced an embanked channel with a regular cross-section, and an over-wide channel at low flows. Other changes in the long profile of the channel, such as the addition of weirs and bedchecks to the river system reducing the long section gradient, have reduced velocities further increasing deposition. In the focus area there are 4 large weirs (in excess of 1.5 metres) and 10 smaller structures (weirs and bedchecks less than 1.5 metres), reducing the total fall through the focus reach by approx. 18 m., and reducing a natural average slope of 0.003m/m to a modified average slope of 0.0021m/m.

Deposition of fine sediment acts marginally to decrease channel capacity to carry flood flows, and increases the overburden on banks, berms and embankments, decreasing stability, and increasing the risk of failure. There is a significant associated maintenance cost to address these problems, (see Table 4.1 below). Additionally, the fine sediment deposition impacts upon conservation and fisheries interests, as it cloaks the river-bed environment, reducing habitat quality for invertebrates, macrophytes and fisheries. The current methods used to manage the sediment problem are those of 'engineering practice', i.e. the dredging of sediments from the channel and the scraping of sediments from banks and berms.

It is difficult accurately to determine the natural bed composition of the River Mersey through the focus reach, such is the length of history of modification that it has undergone. However, as a river reach with a large, predominately upland, catchment it is not unreasonable to infer that it might have a natural bed surface of predominately fine gravels. A useful comparison might be drawn with the River Eden which has a similar catchment area, draining predominantly upland terrain, but is one of the last large river catchments in this country to be predominantly unmodified by engineering for virtually all of its length. In its most comparable area to the Mersey focus site (i.e. its middle reaches between Appleby and Carlisle the Eden has a bed composition of medium/fine gravel (with a median diameter in the range 20-40 mm).

UNIVERSITY OF SOUTHAMPTON LIBRARY

Table 4-1: Summary of Maintenance Costs Associated to Fine Sediment Deposition

Estimated cost of fine sediment associated works[7] 1996/97	Estimated cost of fine sediment associated works 1997/98	Estimated typical cost of fine sediment associated works per annum	Estimated cost of fine sediment associated works as a proportion of total maintenance budget for focus site[8]
£ 80,000	£60,000	£70,000	41%

4.2 Flood History of the Upper Mersey Catchment

The Mersey focus site has a wide, flat floodplain that has attracted settlement and cultivation for many centuries; therefore the area has a long history of flooding, and there are many accounts of such events in existence, from contemporary evidence such as newspaper reports, and from an extensive compilation of documentary and verbal accounts. This evidence has been drawn together in the report by Scott Wilson Kirkpatrick & Co. (1999a), and Table 4.2 below gives a summary of this work. The comparative increase in recorded events given in the Table in the 20th century is symptomatic only of the availability of greater records for recent years, and not necessarily of any significant hydrological trend.

The earliest record of flooding in the catchment is from circa 1700, when the records of Stretford Manor show 'raising, thickening and mending of the banks of the Mersey after flood damage'. Not surprisingly many of the events that are recorded in Table 3.1 (Flood History of the Glossop catchment) in the previous case study are also mirrored in the table below, (e.g. the events of 1799, 1938, 1944, 1956, 1965, 1973, 1987, 1991 and 1992). However, the Mersey has a much larger catchment area than the Shelf

[7]Fine sediment deposition is cited as the prime cause of 'heavy maintenance' (eg. removal of overburden from banks and berms) works on the focus area of the Mersey. Information source: Personal communications with Alan Unsworth (Agency), 5.11.98 - Flood Defence, Maintenance with responsibility for Mersey.

[8]Derived by taking a mean average of total spend for site over years 96/97 and 97/98.

Brook, (approx 600 sq. km. versus approx. 15 sq. km.), and it contains proportionally less upland watercourses, therefore while it is still occasionally susceptible to 'flash' floods from convective summer thunderstorms (particularly in its upper reaches), at a catchment wide level it is more susceptible to flooding from prolonged periods of rain, often over the winter months. This is probably the reason why 'the Great Peak Flood' that effected the Shelf catchment in 1930 is not recorded as an event in the Mersey flood record, and the 1944 summer flood event (thunderstorm), which affected the Shelf Brook dramatically, was not an event at this catchment scale.

Table 4-2: Flood History of the Mersey Catchment

Date	**Climatology**	**Documented Comments**
c.1700	Winter Flood	Embankment repairs required after flooding.
1799	Winter Flood	Widespread flooding.
c.1800	Winter Flood	Flood damaged Bridgewater canal viaduct.
1872	Summer Flood	Flood damage amounting to £11,000 in Mersey district.
1938	Summer Flood	Flooding recorded in Manchester suburbs of Heaton Moor, Cheadle and Hazel Grove.
1944	Winter Flood	Flow of 267 cubic metres recorded at Irlam.
1956	Summer Flood	Highest water levels since 1799 recorded, widespread flooding in Withington (Manchester) observed.
1965	Winter Flood	Mersey, Goyt and Tame reached highest levels in 20 yrs. Sale Ees flood basin operated.
1968	Winter Flood	Stockport, Marple and Macclesfield flooded, Marple town centre under 2 ft. of water.
1973	Summer Flood	Most extensive flooding of Mersey catchment watercourses in 20^{th} century, flooding recorded at Woodley, Romiley, Cheadle, Hazel Grove, Brammall, Moor End, Brook Bottom, Compstall, Lyme Hall, Stockport and Poynton.
1981	Summer Flood	Flooding in upper Mersey catchment, 110 properties flooded.
1987	Summer Flood	250mm rain in 24 hours in Manchester, trading estate in Cheadle Hulme flooded.
1991	Winter Flood	20 houses and 3 pubs flooded on River Etherow, 10 houses flooded by Black Brook and River Goyt .
1992	Winter Flood	Flood flow with estimated return of 1 in 15 years on River Etherow.

4.3 Catchment Characteristics

The Mersey basin forms the largest catchment in NW England, containing the sub-catchments of the Rivers Goyt, Tame, Etherow, Bollin, and Weaver. The Mersey flows east to west from the hills of the southern Pennines and northern Peak District through the conurbation of greater Manchester, across the Cheshire plain to its estuary in the Merseyside conurbation of Liverpool and Birkenhead. The area under consideration in this case study is 'upper Mersey catchment' comprising the sub-catchments of the Tame, Goyt Etherow and a number of smaller tributaries of which the most significant is Micker Brook.

The catchment area of the upper Mersey contains a very wide range of landuses, from grouse moors and rough grazing in the headwaters to extensive industrial and urban developments in the area of the Manchester Conurbation. The combination of upland headwaters, with high precipitation and relatively steep slopes, and predominately non-cohesive sandy bank materials, means that the watercourses of the upper Mersey catchment have been historically the focus of fairly dynamic geomorphological change. However, the history of flood defence and channel management, as indicated above, has sought to reduce such dynamism. The principal characteristics of the upper Mersey catchment are summarised in Table 4.3 below. A summary of peak flows at different return periods is given below in Table 4.4, and a summary of information pertaining to the sediment characteristics at the flood defence focus site is given in Table 4.5, (the small size of the sediments at this site means that it is not possible to give a breakdown of A, B and C axis dimensions as in the case of the Shelf Brook Case Study).

Table 4-3: Upper Mersey Catchment Characteristics Summary

Study Area	600 km^2
Mainstream Length	149 km (main rivers and significant tributaries).
Average Slope[4] (m/m)	0.0021
Sinuosity[4]	1.4 (maximum 2.5)

Principle Tributaries	Tame, Goyt, Etherow, Micker Brook.
Valley Description[9]	Extensive floodplain in natural state, largely divorced from channel by history of flood defence works.
Bank Stability	Non cohesive throughout majority of catchment, containing high proportion of cobbles and gravels in headwater reaches, principally sands and sandy soils in lower reaches, with occasional gravel lenses.
Bed Stability[4]	Unstable, prone to frequent deposition and movement.
Bed Texture[4]	Sands / silts.
Geology (Solid)	Millstone grit series, Palaeozoic sandstones and shales.
Geology (Drift)	Peats and recent alluvial deposits, some boulder clay.
Soils	Raised bog and Blanket Peat, Coarse sandy loams, sea.
Landscape	Headwaters open moorland and rough grazing, lower reaches extensive urban development, improved pasture, some arable farming and limited managed woodland.
Management History	Extensive.

Table 4-4: Summary of Mersey Modelled Peak Flows[10]

Site Description	**Grid. Ref.**	**1 in 10 year return flow m^3/s**	**1 in 50 year return flow m^3/s**	**1 in 100 year return flow m^3/s**
River Tame at Staleybidge	SJ 964 985	64	90	102
River Etherow at Broadbottom	SJ 962 908	170	183	192
River Goyt at at Marple Bridge	SJ 964 898	119	203	234
River Mersey at Poynton	SJ 840 890	450	466	475

Table 4-5: Summary of Typical Bed Characteristics at Mersey Flood Defence Focus Site

Stability	Unstable		
Surface Texture	Max = 50mm	Min = 0.002mm	Median = 0.5mm

9 Refers specifically to flood defence focus area
10 Scott Wilson Kirkpatrick 1999a

4.4 Geomorphological Objectives

This case study forms the second part of the efforts to address the objectives as defined in chapter 2 above. The objectives were to develop an audit method and demonstrate its ***versatility*** by applying it to projects in catchments with different physical habitats, catchment sizes, flood defence management objectives and at different flood defence life-stages. In pursuance of these *versatility* objectives the upper Mersey offers a case study that is different from the Shelf Brook Case Study in every way, from the physical attributes of the catchment, to the flood defence management objectives and to the life-stage of the scheme.

This case study will then go on to assess the objectives of *utility* defined in chapter 3 as demonstrating the advantages of the audit over existing methods, identifying any data required (in addition to these collected by the audit) to fulfil different Flood Defence Management objectives, and finally to appraise the tangible benefits of the audit. There were also a number of additional objectives that were identified in the conclusions of the Shelf Brook case study (Section 3.8.2), and these will be considered by this case study.

In terms of the first and second *versatility* objectives, i.e. demonstrating that the audit method is applicable to different physical habitats and to catchments at different scales, the upper Mersey case study complements the Shelf Brook study in providing a catchment that is large in a U.K. context (approx. 600 square kilometers). It also has a wide range of catchment landuses as indicated in Section 4.3 above, and significantly it includes a large proportion of urban area in which the watercourses have been modified and engineered. The ability of the audit methods to include modifications is important as such modifications to watercourses are common at a national scale. The different scale of this case study and the length of watercourses to be assessed will however necessitate the adoption of some different field techniques (these changes are discussed in Section 4.5 below). In particular the possibility of more than one individual collecting the audit data raises issues such as the quantification of between-surveyor variability. In the Shelf Brook Case study it was also concluded that the audit should be tested on the tributaries of a river catchment, in addition to the 'main stem' river system; this will also be considered in the development of methods below, as will the need to include the collection of data on modifications to a watercourse's banks and beds.

Another issue raised in the conclusions of the Shelf case study (Section 3.8.2), particularly pertinent in the case of a large catchment such as the upper Mersey, was the need to apply the audit assessment to the whole length of watercourses. In other words, is it possible to audit only a sample proportion of the whole catchment 'population' of watercourse reaches and still produce the same findings re management application?

The third of the *versatility* objectives, application of the audit to different flood defence maintenance management issues, is pursued in the case study by the application of the audit method to the identification of sediment sources and sinks in the upper Mersey catchment. Provision of this information is of great potential benefit to flood defence managers as once the key sites of sediment input are identified then it is possible to target efforts at reducing sediment supplies at source and thus reduce the long term needs for flood defence maintenance (such as dredging) at the focus site. There are obviously tangible benefits associated with such an application of the audit method and these are discussed separately below. However, as identified in the conclusions of the Shelf Brook Case Study, if such contributions to flood defence management are to be maximized then the data that the audit collects must be augmented. In particular more information is needed on the different types of erosion and deposition occurring, in order to provide more detailed suggestions of how to reduce such inputs / where to target management efforts. More information is also needed on the causes of erosion and deposition and especially any factors which are artificially accelerating rates of such processes.

The fourth *versatility* objective, that of application to different life-stages of Flood Defence schemes, is addressed in this case study by the application of the audit method at project-feasibility stage. This again complements the post-project appraisal application of the Shelf Brook case study in providing an example application that is at the opposite end of scheme development. The opportunity to provide an input using the audit method at this early stage opens the way to increased opportunities to incorporate the findings of the audit in the procedures of the Flood Defence scheme itself. Additionally, the scale of this application means that it may also be possible to use the results to inform not just flood defence maintenance, but also the wider policy and planning functions of Environment Agency operation within the upper Mersey catchment.

In terms of *utility* objectives this case study seeks to 'pick up' where the Shelf Brook case study 'left off'. As concerns the first *utility* objective, i.e. demonstrating the advantages of the audit method over existing methods, the previous case study (Section 3.7.6 established that the audit approach had significant advantages over the existing methods of engineering science (e.g. the use of formulae) and geomorphological science (e.g. the lengthy collection of field data). As was the case with the Shelf Brook, the methods of engineering practice applicable to the Mersey focus site are those that are currently applied, therefore benefits over such methods will be examined as tangible benefits. The Shelf Brook case study did, however, leave a number of questions to be answered concerning the demonstrable benefits of the audit method over various existing methods of geomorphological practice. Therefore there is a need to take the comparison between the audit methods and examples of such methods of geomorphological practice further in this case study, this will be addressed in the methods below.

The second *utility* objective, defining additional data needs was discussed in the last case study in detail as concerns sediment-yields. However, in the case of this study there should be no need for additional data as the flood defence objective, sediment source identification, may be fulfilled using solely the contemporary observations of catchment geomorphological behaviour recorded by the audit.

The final *utility* objective, that of demonstrating the tangible benefits of the audit method, will be investigated in some depth in this case study, as the scale of the application and the fact that the methods are being applied at the initial stages of the flood defence scheme, means that there may be potential to show considerable benefits.

A summary of the application of both the objectives of *versatility* and *utility* in this case study is given in Table 4.6 below, which also includes a précis of the additional issues identified in the Shelf Brook case study.

Table 4-6: Summary of the Application of the Global Objectives to the Upper Mersey Case Study

Global Objective	**Primary consideration in the upper Mersey case study**	**Additional issues to be covered (identified in Shelf Brook case study)**
1. Different Physical Habitats	Varied catchment from uplands >600 mAOD elevation to middle order reaches approx. 30 mAOD Cobble substrate in headwaters to sand/silt bed at focus site Largely non-cohesive bank of alluvial sandy soils Landuse: Urban, Agricultural (arable and grazing), Limited Forestry.	- Need to audit a full catchment system (including tributaries). - Need to use audit in areas of engineering channel modification and structures. - Examine inter-surveyor variability at large catchment scale. - Consider the possibility of reducing coverage of audit to a 'sample' of total reaches.
2. Catchment Size	600 sq.km.	
3. Flood Defence Management Objectives	Identifying catchment sediment sources (both natural and accelerated).	Increase data gathered re types and causes of erosion / deposition.
4. Flood Defence Life-Stage	Feasibility.	
5. Advantages over existing methods	Concentration on comparison with methods of geomorphological practice.	
6. Additional data	Non anticipated as necessary.	
7. Tangible benefits	Positive benefits expected.	

4.5 Development of Methods

4.5.1 Revision of the proforma

To fulfil the geomorphological objectives of this case study a number of changes in the audit approach as presented in the Shelf Brook case study were required. The scale of the audit, (149 km of watercourse), was such that it was impractical, and indeed uneconomic, to collect any data more than these required for analysis purposes. Therefore, compared to the Shelf Brook case study proforma, a number of items were changed:

- Sinuosity and slope were not recorded, as these are map-based features, which may be derived after the collection of field data, if required.
- Information on vegetation and tree cover was removed (over and above that recorded in landuse, see below).
- Data on 'channel associated features' were reduced (such as boulder fields, boulder-berms and scars); as such processes are limited largely to upland headwater watercourses. However, such information is still recorded as different 'types' of deposition ('deposits on the floodplain'), and erosion (e.g. 'mass wasting – slides').
- Data on bedforms, channel form and geometry were removed.
- Most significantly, the time-consuming field assessment of particle size (using the Wolman, 1954 technique), was dropped in favour of a series of tick boxes for 'substrate condition' recording the presence (or extensive presence, i.e. greater than 33% of reach's bed surface) and also whether the bed was consolidated or unconsolidated.
- Reach length was increased to 500 metres. This is comparable with other quantified methods of geomorphological / physical data gathering such as the River Habitat Survey, (Environment Agency, 1997).

However, a significant number of other factors were added to the survey (as detailed below) and shown in Figure 4.2 but local trials of the revised audit method (on the Padgate Brook close the Environment Agency headquarters in Warrington, confirmed that the proforma could be completed on a 500 metre reach in approx. 10 minutes.

The question of what 'level' of tributaries should be included in the audit is difficult to resolve on a rational basis. Such is the size of the upper Mersey catchment that it is obviously possible to include more and more minor watercourses in the catchment area almost ad-infinitum. However, the time (and therefore cost) implications,of 'over-inclusion' must be considered if the tangible benefits of the audit are not to be jeopardised. Therefore it was decided to include within the audit all designated main river, (those watercourses on which the Agency is a statutory consultee over all works to the channel itself or within 8 metres of it). This level of catchment detail was considered appropriate, for while it may be interesting to gain a geomorphological insight into more minor watercourses, it is only main rivers on which the Agency actually has the power to pro-actively influence / implement the findings of this case study.

The audit proforma was also extensively adapted, increasing the amount of data that recorded the influence of existing in-channel engineering and management. The presence and extent of engineering features such as resectioned, culverted, embanked, bermed, two-stage or straightened channel was recorded, in addition to those engineering features specifically for flood defence such as walling or channel enlargement. The impact of such engineering works, or more usually landuses, was also recorded, comprising the noting of any obvious 'causes' of erosion, such as poaching, footpath impact, tipping / building, hydraulic effects of named structures (including previous protection / enhancement measures such as deflectors) and vegetation management. In addition, any obvious 'causes' of deposition such as tipping / building, hydraulic effects of named structures, or modification of channel width were recorded.

The data collected in the proforma were also expanded to include more detailed descriptions of the type of erosion and deposition processes occurring. Including, eroding cliffs, stable cliffs, slumps, toe scour, mass-wasting by slide, creep or wash and bed scour. The range of depositional features was also expanded from those recorded in the Shelf Brook proforma (i.e. mid, side and point bars), to include features such as discrete deposits, and other features of deposition both in the channel, (e.g. deposits on berms), and also floodplain deposits. This extra information was collected, as different management options are appropriate to different forms of erosion and deposition, as discussed in Section 4.7.6

Floodplain landuses which were present, (in any proportion), or extensive, (covered more than a third of the reach length of the 5 metre corridor adjacent to the river bank top), were also included in the proforma in an effort to collect data from which information of diffuse inputs of fine sediment to the channel could be drawn.

An 'overall impression' section and a 'coverage' section were also added to the proforma. The former was designed to retest the findings of the Shelf Brook case study concerning the comparison of 'simple classification' results to 'environmental diagnostics' (i.e. the wider quantified findings collected by the completion of the proforma). Coverage was included because factors of time limitation (see below) impacted on the data collection process. Therefore, it seemed likely that data may have to be collected at times under conditions which might mean that site factors were obscured (e.g. high water levels making it had to determine bed substrate), or in locations in which it was not possible to secure full access rights quickly, e.g. uncommon events such as situations in which land-owners refused permission to enter their property.

Keynotes were devised to accompany the revised audit proforma to provide simple definitions of the different geomorphological features to be recorded in the field. Both the revised proforma and the keynotes are shown in Figure 4.2

4.5.2 Site observations and proposed analytical developments

The scale of the audit meant that it as not possible for a single observer to undertake the fieldwork and produce results that were within the timeframe available in the feasibility phase of the Mersey Flood Alleviation Scheme (6 weeks). Therefore, the lack of available trained geomorphological manpower within the Environment Agency meant that it was necessary to retain consultants to collect the field data, (described below).

Figure 4-2: Upper Mersey proforma and Key Notes

CATCHMENT GEOMORPHOLOGICAL EVALUATION: (1) SEDIMENT SINKS AND SOURCES

To be performed over a 500m channel length

A. SITE INFORMATION

Catchment:	Water course:	Reach number:	Date:	Surveyor:	Photo number:	Grid reference:	Adverse conditions:

Map location recorded:	Site surveyed from: left bank ☐	right bank ☐	channel ☐	Additional notes:

B. EROSION FEATURES

Scale (m²)	Eroding cliff (E1)					Stable cliff (E2)				
	Clay/silt	Sand/gravel	Cobble/boulder	Bedrock	cause	Clay/silt	Sand/gravel	Cobble/boulder	Bedrock	cause
macro										
meso										
micro										

Scale (m²)	Slump (E3)					Toe scour(E4)				
	Clay/silt	Sand/gravel	Cobble/boulder	Bedrock	cause	Clay/silt	Sand/gravel	Cobble/boulder	Bedrock	cause
macro										
meso										
micro										

Scale (m²)	Mass wasting - Creep (E5a)					Mass wasting - Slide (E5b)				
	Clay/silt	Sand/gravel	Cobble/boulder	Bedrock	cause	Clay/silt	Sand/gravel	Cobble/boulder	Bedrock	cause
macro										
meso										
micro										

Scale (m²)	Mass wasting - Wash (E5c)					Bed scour (E6)				
	Clay/silt	Sand/gravel	Cobble/boulder	Bedrock	cause	Clay/silt	Sand/gravel	Cobble/boulder	Bedrock	cause
macro										
meso										
micro										

NB Scale of features: macro-scale > 10m²; meso-scale = 1m² - 10m²; micro-scale < 1m²; circle features with accelerated erosion, and sequentially record cause.

C. SUBSTRATE CONDITION

	Cons	Uncons		Cons	Uncons
Clay/silt			Sand/ gravel		
	Cons	Uncons		Cons	
Cobble/ boulder			Bedrock		

NB (tick) present; (E) extensive > 33% of reach

D. ENGINEERING

length of channel (L / R)	Resectioned	Culverted	Embanked	Two-stage	Bermed	Straightened	Reinforced1	Reinforced2	Reinforced3
0 none									
1 1 - 85m									
2 85 - 166m									
3 166 - 333m									
4 333 - 500m									

E. DEPOSITIONAL FEATURES

Scale (m²)	Point bar (PB)				Mid-channel bar (MB)			
	Clay/silt	Sand/gravel	Cobble/boulder	cause	Clay/silt	Sand/gravel	Cobble/boulder	cause
macro								
meso								
micro								

Scale (m²)	Side bar (RB)				Other form of discrete deposit (DD)			
	Clay/silt	Sand/gravel	Cobble/boulder	cause	Clay/silt	Sand/gravel	Cobble/boulder	cause
macro								
meso								
micro								

Scale (m²)	Deposit on berms (BM)				Deposit on floodplain (FP)			
	Clay/silt	Sand/gravel	Cobble/boulder	cause	Clay/silt	Sand/gravel	Cobble/boulder	cause
macro								
meso								
micro								

NB Scale of features: macro-scale > 10m²; meso-scale = 1m² - 10m²; micro-scale < 1m²; circle features with accelerated deposition, and sequentially record cause; record stability of deposits: U = unstable; P = partially stable; S = stable.

F. FLOODPLAIN LANDUSE

Landuse	Broadleaf/ mixed wood	Coniferous plantation	Orchard	Moor/heath	Scrub	Tall herbs	Rough pasture	Improved grassland*	Improved grassland**	Tilled land	Wetland	Open water	Suburban/ urban	Rock and scree	Quarrying/ mining	Road, track, footpath/brid
Effect on sediment budget																

NB record all uses within 5m of banktop and/or any further uses from the channel that contribute to the sediment budget; (tick) present; (E) extensive > 33% of reach; circle if stock-proofed.

G. FLOOD PROTECTION

Protection	Landuse	Restoration potential
Embanked		
Concrete walled		
Drystone walled		
Artifically enlarged+		

H. FLOODPLAIN WETLANDS

Scale (m²)	Dry relict channels	Back swamp	Oxbow lake	Levees	Marsh	Carr	Flush	Bog	notes
macro									
meso									
micro									

NB Scale of features: macro-scale > 10m²; meso-scale = 1m² - 10m²; micro-scale < 1m²; circle features with visible sediment deposition; only record features visible from banktop.

I. OTHER FEATURES

Tributaries		Outfalls	
macro		macro	
meso		meso	
micro		micro	
Fords			

NB Scale of features: macro > 10m; meso = 1m - 10m; micro < 1m; circle features with significant sediment input.

J. OVERALL IMPRESSION

Provide an assessment of your overall impression of the 500m reach, where:

	0	1	2	3
Sediment source				
Sediment sink				
Sediment transfer				

0 absent
1 local
2 abundant
3 extensive

K. COVERAGE

% of reach surveyed:

0 - 33	☐
34 - 66	☐
67 - 100	☐

* Improved grassland (no stock use, eg. Amenity)
** Improved grassland (stock use, enclosed)
\+ Artificially enlarged (widened, deepened)

A. SITE INFORMATION

Catchment	Major sub-catchment of the Mersey
Water course	Named river, stream or brook (see maps)
Date	Day of survey
Surveyor	Either R. McInnes (RM) or G. Hammond (Gene)
Photo number	Minimum of one photo per reach
Grid reference	OS grid reference
Adverse conditions	Factors preventing or influencing survey, e.g. heavy rain, river in spate, access problems
Map location recorded	Not used
Site surveyed from	Either bank or channel
Additional notes	Any other notes of importance

B. EROSION FEATURES

The presence of a feature is indicated by a tally mark. Where accelerated erosion is present the tally mark is circled and the cause sequentially noted.

Features

Eroding cliff (E1)	Predominantly vertical or near vertical cliff showing a clean earth face
Stable cliff (E2)	Not recorded as not currently contributing to the sediment budget of the system.
Slump (E3)	Unvegetated or partially vegetated slump blocks or debris associated with eroding cliffs.
Toe scour (E4)	Undercutting and scour at the toe of banks.
Mass wasting - Creep (E5a)	Sediment input to channel from soil creep from adjacent valley slopes.
Mass wasting - Slide (E5b)	Sediment input to channel from slide material derived from adjacent valley slopes.
Mass wasting - Wash (E5c)	Sediment input to channel from surface wash of material from adjacent valley slopes.
Bed scour (E6)	Active scour and downcutting of the river bed.

Scale of features:
macro-scale > $10m^2$
meso-scale = $1m^2$ - $10m^2$
micro-scale < $1m^2$

Accelerated erosion causes

Poaching (P)	Damage to banks and river margins due to stock.
Footpath (F)	Damage to banks and river margins by walkers, fishermen, horse riding, etc.
Urban activities (U)	Damage to banks and river margins by fly tipping, building activities, garden waste, etc.
Hydraulic change (H)	Damage to banks and river margins due to a change in hydraulic properties caused by a weir, bridge, culvert, etc.
Deflection (D)	Damage to banks and river margins due to a change in hydraulic properties caused by deflectors.
Vegetation management (V)	Damage to banks and river margins accelerated by, or directly due to, vegetation management practises.

Bank material — All taken from RHS spot check key.
Clay / Silt
Sand / Gravel
Cobble / Boulder
Bedrock

C. SUBSTRATE CONDITION

Ticked if present, E if extensive (>33% of the reach)

Substrate material — All taken from RHS spot check key.
Clay / Silt
Sand / Gravel
Cobble / Boulder
Bedrock

NV	Not visible
Consolidated	Weed or algae covered, compacted and stable.
Unconsolidated	Unvegetated, clean, loose and unstable.

D. ENGINEERING

Length of channel subjected to engineering recorded (Left bank | Right bank).

Engineering structures
Resectioned
Culverted
Embanked
Two-stage
Bermed
Straightened
Reinforced (1) Whole bank
Reinforced (2) Reinforced toe
Reinforced (3) Reinforced top

Length of channel	
0	none
1	1 - 85m
2	85 - 166m
3	166 - 333m
4	333 - 500m

E. DEPOSITIONAL FEATURES

The presence of a feature is indicated by a tally letter. Where accelerated deposition is present the tally letter is circled and the cause sequentially noted.

Features

Point bar (PB)	Located on inside of meander bend, sloping gently into the channel.
Mid-channel bar (MB)	Distinct depositional feature within the channel of material derived from the channel and exposed at low flows.
Side bar (SB)	Distinct depositional feature, at the foot of the bank, of material derived from the channel and exposed at low flows.
Other discrete deposit (DD)	Other sediment deposits such as material deposited on islands, behind debris dams or bridge supports, etc.
Deposit on berms (BM)	Distinct depositional features on berms adjacent to the channel.
Deposit on floodplain (FP)	Overbank depositional features on adjacent floodplain surface.

Scale of deposits
macro-scale > $10m^2$
meso-scale = $1m^2$ - $10m^2$
micro-scale < $1m^2$

Stability of deposits
The following letters are used as tally marks, depending on the stability of the deposits:
U Unstable -active deposition with no vegetation present
P Partially stable - vegetation has developed but subsequent active deposition has occurred
S Stable - mature vegetation has developed with no signs of active deposition

Accelerated dposition causes

Urban activities (U)	Sediment accumulation due to fly tipping, building activities, garden waste, etc.
Hydraulic change (H)	Sediment accumulation due to a change in hydraulic properties caused by a weir, bridge, culvert, etc.
Channel width change (W)	Sediment accumulation due change in hydraulic properties associated with a change in channel width.

Deposited material — All taken from RHS spot check key.
Clay / Silt
Sand / Gravel
Cobble / Boulder

F. FLOODPLAIN AND ADJACENT LANDUSE		2 of 2
All land uses within 5m of bank top, or further if they influence directly th edelivery of sediment to the channel, are recorded. Ticked if present, E if extensive (>33% of the reach).		
Landuse		
Broadleaf / mixed woodland	**Improved grassland***	No stock use, amenity grassland
Coniferous plantation	**Improved grassland****	Stock use
Orchard	**Tilled land**	
Moor / heath	**Wetland**	
Scrub	**Suburban / urban**	
Tall herbs	**Rock and scree**	
Rough pasture	**Quarrying / mining**	
	Road, track, footpath	

G. FLOOD PROTECTION		
Where present, type of flood protection is recorded.		
Protection	**Restoration potential**	
Embanked	**Yes**	Possible to restore connection between channel and floodplain
Concrete wall	**Minimal**	Limited opportunity to restore connection
Drystone wall	**No**	No opportunity to restore connection
Artificially enlarged channel		

H. FLOODPLAIN FEATURES		
Where present, floodplain features that acts as sediment traps are recorded. These features are to be observed from the bank top.		
Features		
Dry relict channels	**Marsh**	**Scale of features:**
Back swamp	**Carr**	macro-scale > $10m^2$
Ox-bow lake	**Flush**	meso-scale = $1m^2$ - $10m^2$
Levee	**Bog**	micro-scale < $1m^2$

I. OTHER FEATURES	
Other features that are acting as sources of sediment are recorded.	
Features	
Tributaries	Tributary channels delivering an active sediment load to the main channel
Outfalls	Outfalls delivering an active sediment load to the main channel
Fords	Vehicular or animal river crossings delivering sediment to the channel

J. OVERALL IMPRESSION		K. COVERAGE
Subjective overall impression of the 500m reach in terms of its function as a sediment source, sink or transfer system.		% of reach where it was possible to survey.
Function		
Absent (0)	No evidence	
Local (1)	Occasional or localised (<33% of reach)	
Abundant (2)	Common (33% to 66% of the reach)	
Extensive (3)	Frequent (>66% of the reach)	

The appointment of the consultants raised questions concerning the consideration of the confidence limits pertaining to the consistency of data collection between observers; this was addressed in two ways.

Firstly, a repeat survey of a sub-sample of sites by different observers was undertaken and the variability was analysed. Secondly, a 'micro-meso-macro' scaling system was adopted to simplify the estimates of areas of erosion and deposition in the field, and reduce the variability of such estimates between observers. Using this scale an area of less than 1 square metres of erosion or deposition was recorded as one micro feature. An area of 1 – 10 square metres was recorded as a meso feature, and an area greater than 10 square metres was recorded as a macro feature. Features were recorded by bank / bed substrate type, (clay/silt, sand/gravel, cobble/boulder and bedrock), and any one reach could have any number of discrete occurrences of micro – meso – macro erosion or deposition recorded. This method of recording features of erosion and deposition was adopted as there is evidence to suggest, (Environment Agency 1997), that estimates by eye vary so significantly even between trained observers, that the recording of estimated areas of erosion and deposition may not be methodologically robust. This decision increased the potential speed of surveys, but also meant that all results would return only ranges of erosion and deposition observations and not single figures per site. This meant that it would not be possible to derive 'yield figures', as in the case of the Shelf Brook case study. However, as the flood defence objective was primarily to identify 'hotspot' sediment sources, it was considered that this could be undertaken successfully using the ranges that this method would produce (as detailed in the discussion of results, Section 4.7.1).

The consideration of whether it is possible to apply the audit technique to only a sample of the total length of watercourses in the study area was investigated during the analysis of data by selecting sampling densities less than 100% coverage (i.e. using densities of 25 or 50%), and by selecting sites in such reduced densities first randomly and secondly on an 'interval' basis (i.e. every second site or every fourth site).

The Shelf Brook case study indicated that there were other methods of geomorphological practice that, if applied, may have produced similar findings to the audit methods devised in that case study, i.e. Catchment Baseline Audit, Fluvial Audit and possibly River Habitat Survey. Therefore it was deemed necessary to undertake a comparison with existing survey techniques of catchment evaluation. The implications of time and cost (given the size of the upper Mersey catchment, and the required deadline for geomorphological inputs to the flood defence scheme), meant it was only practical to test one such method. Therefore, the most widely applied Environment Agency data collection method for physical riverine, was selected, that of the River Habitat Survey (RHS) technique. This comparison was additionally thought useful as the RHS database is a significant national information resource, and this comparison may help in managing efforts to 'benchmark' its utility for the provision of geomorphological information for engineering management.

As indicated in Section 4.4 above, given the flood defence objectives of the application of geomorphology in this case study, there should be little need for the use of 'additional data' in terms of geomorphological methods etc. to apply the findings of the audit to the identification of catchment sediment sources. However, methods to assess the utility of 'constant reach length definitions' verses 'data-defined reach length definitions' will be considered in that a basic 500 metre reach unit will be used as the starting point for survey, but such units will be agglomerated into continuous ('macro') reaches for management purposes by identifying geomorphological activity and inactivity. Conclusions will be drawn on the size and distribution of such macro reaches in the discussion of results.

Finally the immediate application of the data that are collected in this audit exercise, the scale of the catchment area covered, and the size of the flood defence maintenance costs associated with the Mersey Flood Alleviation Scheme all mean that there is good reason to illustrate the tangible benefits of this geomorphological audit in some detail. Therefore, the discussion of results will seek to provide working examples of these benefits.

4.5.3 Data collection details

To address the methodological developments presented above a new audit proforma was designed as detailed above. The author designed the original contents of this proforma, the Excel format was produced by the project consultants (see below), and the consultants augmented the contents after initial field-testing.

An audit of 149km length of the Rivers Tame, Etherow, Goyt and their tributaries was therefore undertaken at two levels:

A. Geomorphological Audit Sites: The entire main river length was assessed.

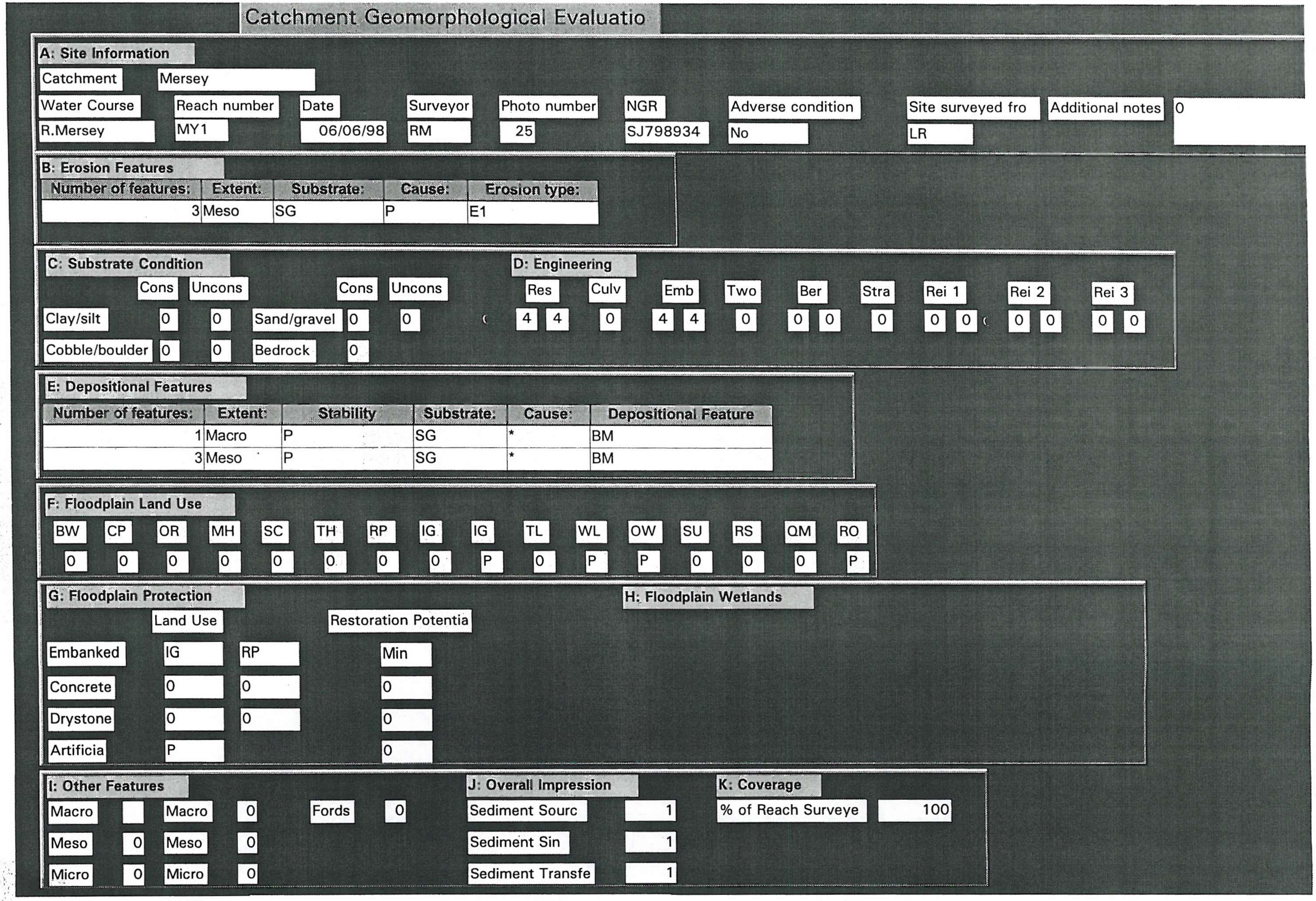
B. River Habitat Survey Sites: 25 km. total stream length were surveyed in detail using standard RHS technique (Environment Agency, 1997), (data collection proforma included in Appendix 1), by RHS accredited surveyors, (forming 50 sites). The author selected the locations of these sites, which were randomly distributed within the survey area.

The survey was not extended to include watercourses upstream of significant impoundments, such as the River Etherorw upstream of the Longdendale dams, certain elements of the upper River Tame and the Rive Kinder upstream of Kinder reservoir. Such reaches were excluded as the vast majority of sediments eroded and transported from such reaches will be trapped in the reservoirs behind the dams, and will therefore not be contributing to the fine sediment accretion problem at the flood defence focus site.

As discussed above, due to the scale of the data collection exercise, and the working timescale for input to the Flood Alleviation Scheme (6 weeks), it was necessary to retain consultants to undertake the majority of the fieldwork. The project was let in accordance with Environment Agency standard terms and conditions as a single contract and a fixed cost quotation. The Consultants appointed were Penny Anderson Associates of Buxton, Derbyshire. The project team consisted of Rob McInnes, (project manager and surveyor) and Gene Hammond (surveyor). The contract was awarded on Monday 27th April 1998, the consultants completed all RHS and geomorphological survey work, and delivered the data on Monday 8th June 1998. Primary analysis of the survey proformas was undertaken by the author during June-July 1998, culminating in the production of a geomorphological assessment as part of the Mersey Flood Alleviation Scheme, (Walker, 1998c). Subsequent analysis has been undertaken as part of this case study.

4.5.4 Data processing

All field data were input to a custom-designed Access database for storage, manipulation and processing, (see Figure 4.3 below). This database was developed because of the scale of the upper Mersey audit information collected, i.e. 55 observations per proforma over 149 sites = approx. 8200 data entries. All the data had to be transferred to digital format for interpretation and analysis whether using a spreadsheet (Excel), statistical package (Minitab) or Geographical Information System [GIS] (MapInfo), as shown in the results and discussion of results below. The easiest way to process and query digital data are to store it in a database, which can then be used to export data sets in any format – be it column data of 'value x per reach' for spreadsheet or statistical analysis or grid reference data / value associations for GIS input. The data-processing staff of the Environment Agency River Habitat Survey Lead Region office undertook this input of the hand-recorded proforma data submitted by the consultants. The links for output data from the database to the various interpretation packages were not automated as this would have required the preparation of script of code to perform such functions which would have either been time consuming or expensive (if professional services had been retained). Therefore, the outputs from the database were simply files of comma-separated data or text format data as required.



Catchment Geomorphological Evaluatio

A: Site Information

Catchment: Mersey

Water Course	Reach number	Date	Surveyor	Photo number	NGR	Adverse condition	Site surveyed fro	Additional notes
R.Mersey	MY1	06/06/98	RM	25	SJ798934	No	LR	0

B: Erosion Features

Number of features:	Extent:	Substrate:	Cause:	Erosion type:
3	Meso	SG	P	E1

C: Substrate Condition

	Cons	Uncons		Cons	Uncons
Clay/silt	0	0	Sand/gravel	0	0
Cobble/boulder	0	0	Bedrock	0	

D: Engineering

Res	Culv	Emb	Two	Ber	Stra	Rei 1	Rei 2	Rei 3
4 4	0	4 4	0	0 0	0	0 0	0 0	0 0

E: Depositional Features

Number of features:	Extent:	Stability	Substrate:	Cause:	Depositional Feature
1	Macro	P	SG	*	BM
3	Meso	P	SG	*	BM

F: Floodplain Land Use

BW	CP	OR	MH	SC	TH	RP	IG	IG	TL	WL	OW	SU	RS	QM	RO
0	0	0	0	0	0	0	0	P	0	P	P	0	0	0	P

G: Floodplain Protection

	Land Use		Restoration Potentia
Embanked	IG	RP	Min
Concrete	0	0	0
Drystone	0	0	0
Artificia	P		0

H: Floodplain Wetlands

I: Other Features

Macro		Macro	0	Fords	0
Meso	0	Meso	0		
Micro	0	Micro	0		

J: Overall Impression

Sediment Sourc	1
Sediment Sin	1
Sediment Transfe	1

K: Coverage

% of Reach Surveye: 100

Figure 4-3: Database used for Upper Mersey Data

4.6 Results

4.6.1 Identification of key erosion sources and depositional sinks

Observations of all types of erosion, (E1-E6 as defined in Figure 4.2 above), were recorded in the catchment noting whether they were observed at a 'Macro' scale (>10m^2), 'Meso' scale (1-10m^2), or 'Micro' scale <1m^2). Only erosion features producing substantive quantities of fine sediments are relevant in this analysis, however the nature of the channel banks throughout much of the upper Mersey meant that in practice virtually all erosion features contain a relatively high proportion of fines. Even where banks contain gravel or cobbles, there are still substantial quantities of fines released from the matrix between the coarser particles. The relative proportions of these different bank material types will however be discussed in Section 4.7 below.

An approximate estimate of erosion and deposition at each site was then developed by taking the number of recorded incidences of all types of erosion / deposition and multiplying these scores by 6 for a 'macro' observation, 3 for a 'meso' observation and 1 for a 'micro' observation. The objectives and methods of the ‘micro-meso-macro scoring system were presented in Sections 4.4 and 4.5 above. This technique facilitated the development of 2 dimensionless indexes, one for erosion (scale 0-100), and one for deposition (scale 0-130). *[These two indices are referred to below as 'total erosion score' and 'total deposition score'].* This scoring system seems to favour micro-scale observation, (as 6 x micro = max. 6 m^2, and 1 x macro = min. 10 m^2, however this is deemed valid as the possibility for development of 6 individual observations of micro scale erosion is likely to be greater than that of a single macro-scale observation). The distribution of the observations of erosion and deposition between the categories of micro, meso and macro scale features is presented in Figure 4.7 below.

There were very few cases of missing data in the audit data, only 7 reaches returned proformas with less than 100% coverage or with any comments in the adverse conditions box. The reaches were simply discounted. The completeness of the data were due to the fact that data collection was undertaken in late spring / early summer during a period of relatively fine weather and low flows.

The distribution and severity of erosion sources and deposition sinks was then plotted throughout the catchment, and the results are shown in the two figures below (4.4 & 4.5).

A series of sensitivity tests was then undertaken on the primary dataset, i.e. the processed erosion data. (This is the primary dataset as the first objective of this case study is to identify sediment sources across the catchment). Plots of the distribution of erosion across the catchment were made using 50% and 25% samples of the full dataset using an 'interval' selection method, (i.e. every other or every fourth site sequentially along the individual limbs of the river network. For the sake of continuity these results will be presented as covered in Section 4.7 as Figures 4.11 and 4.12. Plots were also made using 25% and 50% samples using a random sampling method, (utilising the MINITAB random number generation facility to select sites). These results are also shown in Section 4.7, (in Figures 4.13 to 4.14).

A comparison of scores recorded for sediment sinks and sources in the 'overall impressions' section of the proforma, (as shown in Figure 4.16 below), was also sought by plotting the classes of 'absent, local, abundant and extensive sediment sources and sinks'. This appraisal is a simple classification, as first introduced in the Shelf Brook Case study (Section 3.5.1 Again these results will be presented as they are discussed in Section 4.7.

To compare the results of the audit methods to another technique of geomorphological practice, as described in the Methods above (Section 4.5), the distribution of erosion as recorded by the standard RHS methodology was also sought. Therefore a plot was derived for erosion across the catchment using the 66 RHS sites that had been collected as part of the national RHS database and this data-gathering exercise. This set of upper Mersey RHS data forms close to a 25% sample of the total stream network (149km). The RHS data, (33km covered in total), contains a series of 10 spot-check observations (spaced at 50m. intervals) for each site, each of these observations records the absence or presence of eroding or stable cliffs at both left and right banks. These features are respectively defined as follows. "Bankface predominately vertical or near vertical, with a min. height of 50cm, and showing a clean earth face". "Bankface predominantly

Figure 4-4: Sites of Active Erosion in the Upper Mersey Catchment

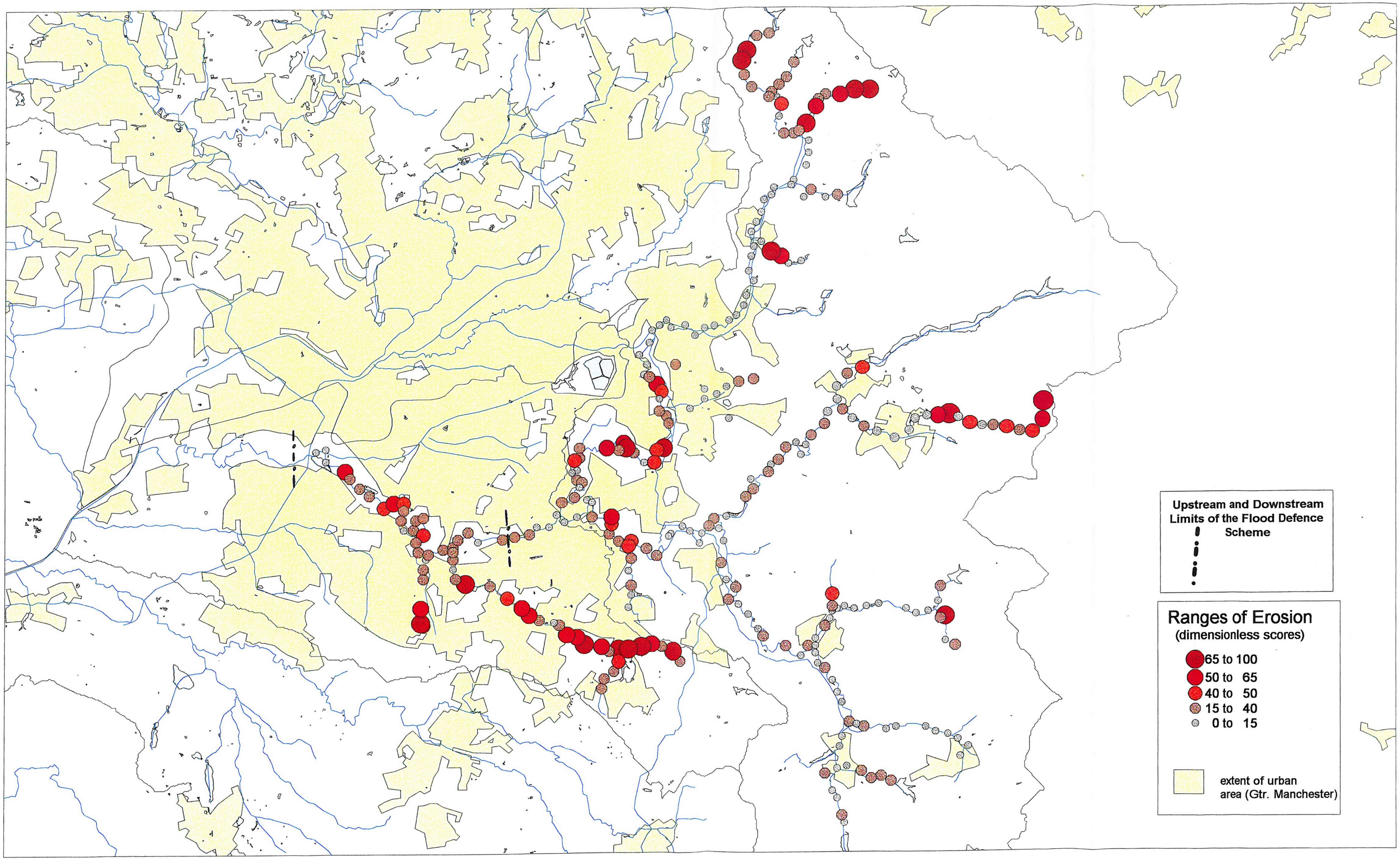
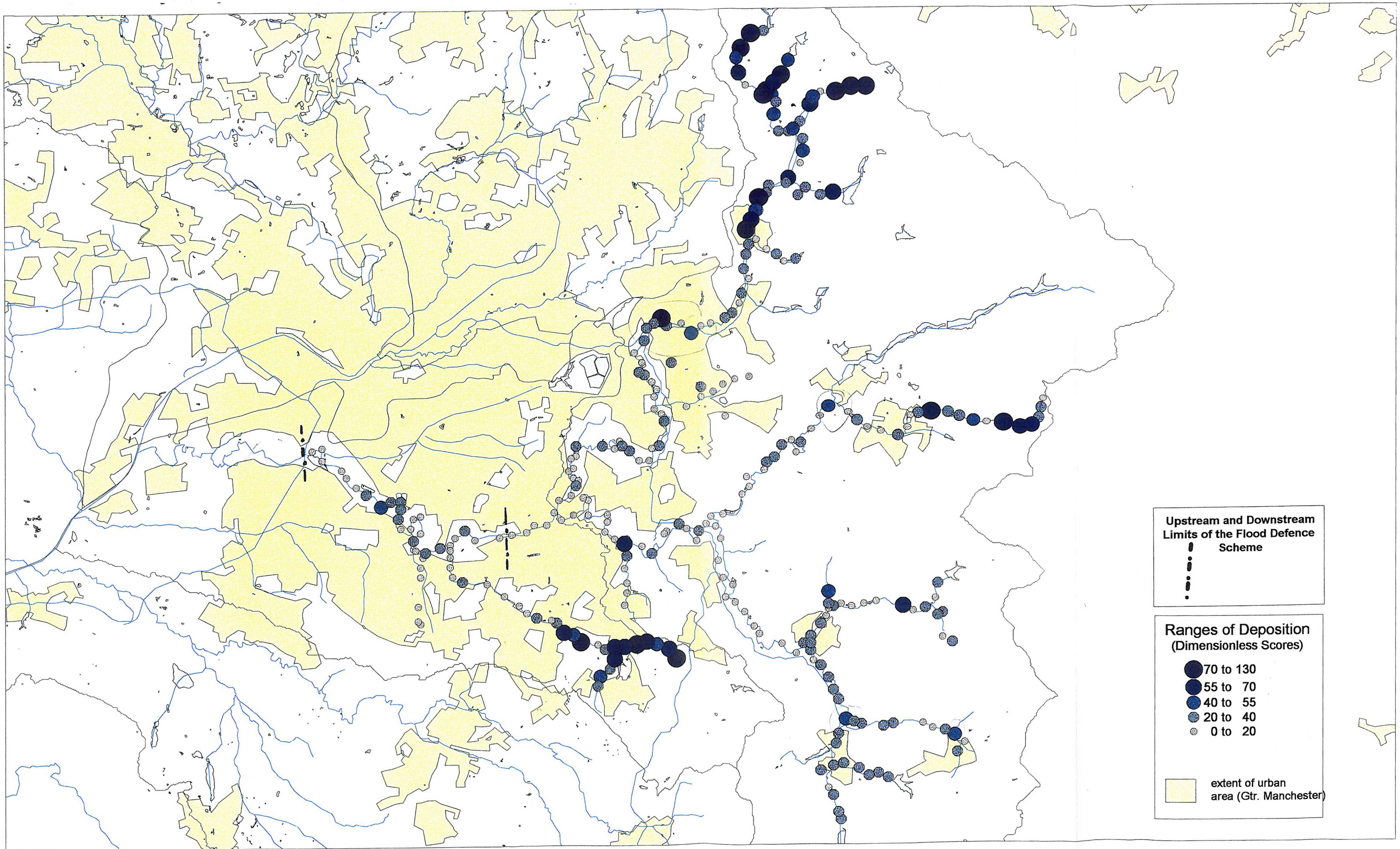


Figure 4-5: Sites of Active Deposition in the Upper Mersey Catchment



vertical or near vertical, with a min. height of 50cm, and without obvious signs of recent erosion", (Environment Agency, 1997, p.21). Therefore a range of site scores (0-20) was calculated by noting the number of erosion observations per site (eroding or stable cliffs), these were converted to percentage figures and the results were plotted. Again, for the sake of continuity these results are shown in the discussion of results where they are discussed in more detail, (Figure 4.17 below).

4.6.2 Causes of erosion and deposition

The catchment data were assessed for recorded causes of erosion and deposition. The findings are summarised below in Tables 4.7 and 4.8, and are discussed in full in Section 4.7.

Table 4-7: Causes of Erosion in the Upper Mersey Catchment

Cause[11]	**% of total observations of erosion**
No obvious immediate artificial cause	77%
Adverse impact of in-channel deflectors	0.2%
Footpaths	11%
Hydraulic Changes	2%
Poaching	7%
Urban Activities	3%
Vegetation Management	0.4%

Table 4-8: Causes of Deposition in the Upper Mersey Catchment

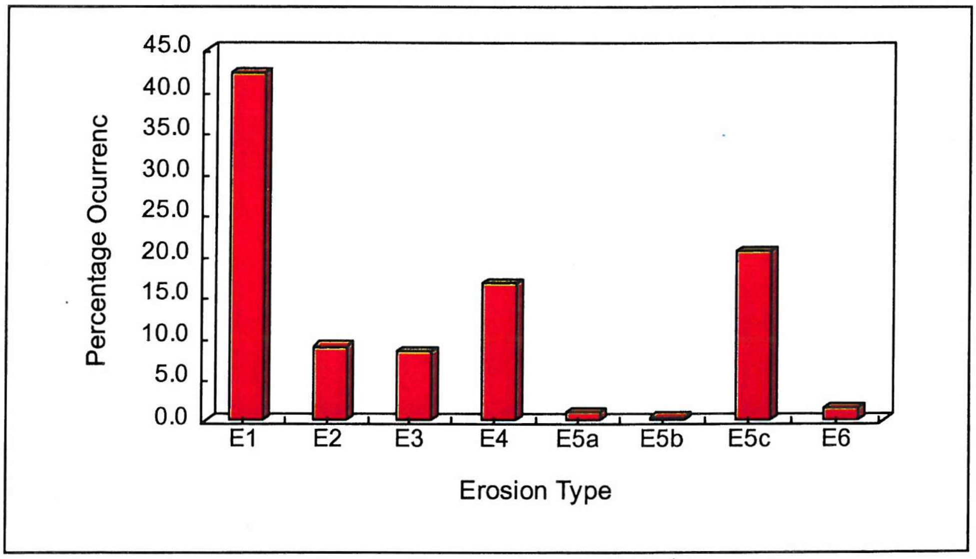
Cause[5]	**% of total observations of deposition**
No obvious immediate artificial cause	93%
Urban Activities	2%
Hydraulic Changes	4%
Channel Width Change	1%

[11]See Figure 4.2 for definitions of causes.

4.6.3 Types of erosion

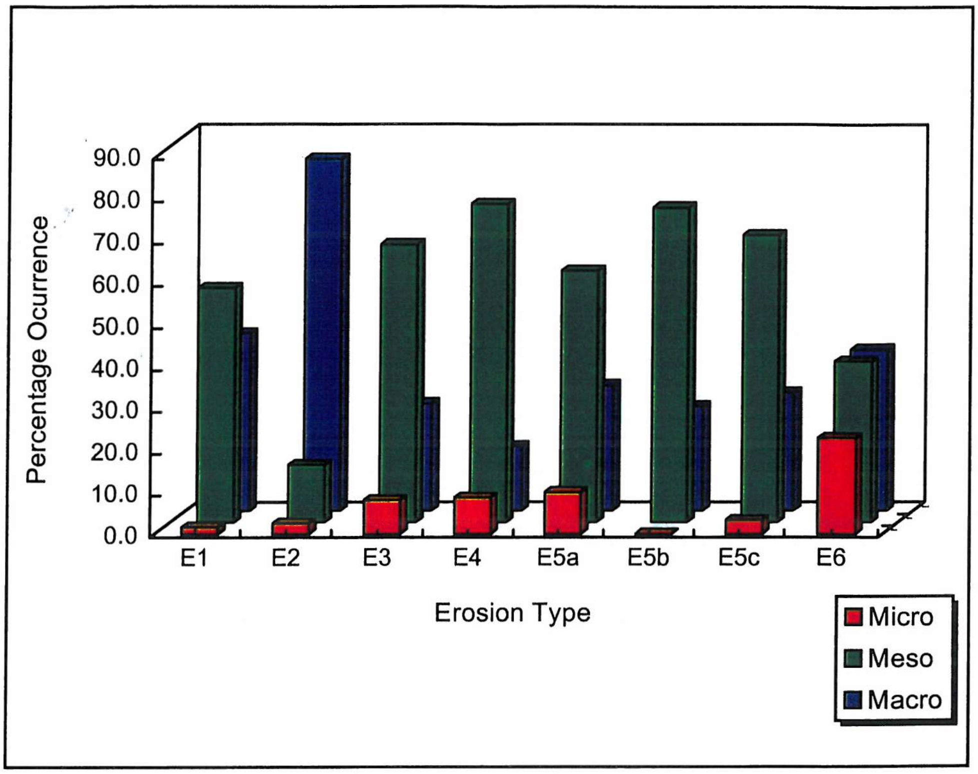
In addition to the extent of erosion, the 'type' of erosion in the upper Mersey catchment was also recorded. To achieve this, observed erosion was separated into 6 basic categories, (described in the legend below and defined in Figure 4.2 above), additionally processes of mass movement were sub-divided into 3 further categories. The distribution of the observed erosion between the different types is shown below in Figure 4.6. The relative distribution between micro-meso and macro scale observations, within the different type categories of erosion, is also shown below in Figure 4.7.

Figure 4-6: Overall occurrence of Erosion by 'Type'



Legend: E1 = Eroding Cliff, E2 = Stable Cliff, E3 = Slump, E4 = Toe Scour E5a = Mass Wasting (Creep), E5b = Mass Wasting (Slide) E5c = Mass Wasting (Wash), E6 = Bed Scour (Photos of typical examples of erosion types are shown in Case Appendix 1, Section 4.9).

Figure 4-7: Occurrence of Erosion by Type at Micro, Meso and Macro Scales



4.7 Discussion of the Findings

4.7.1 Identification of active areas of erosion and deposition

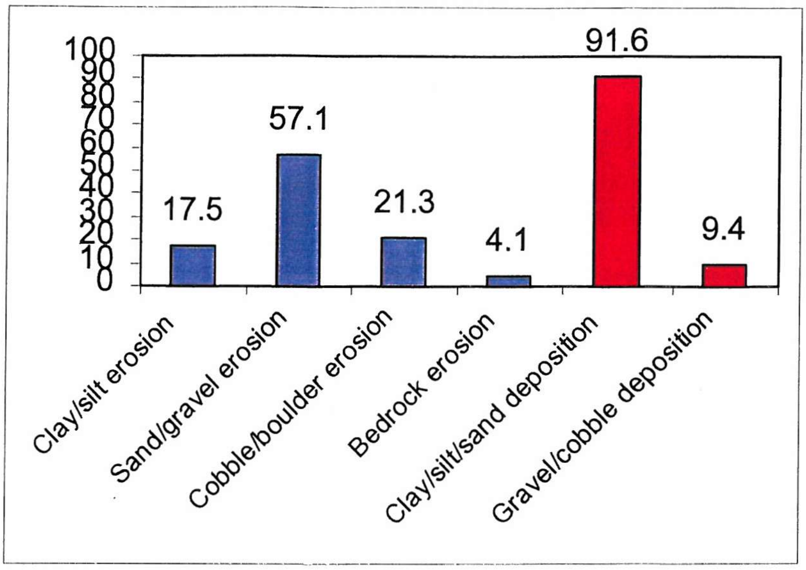
4.7.1.1 Erosion in the Catchment

The examination of erosion within the catchment and the identification of areas which are acting as particularly active sediment sources is key to the flood defence management objectives of this case study, as expressed in Section 4.4 above. The key source areas of sediment production (erosion areas) as expressed in Figure 4.4 above, illustrates the distribution of the most extensively eroding 53 sites in the area surveyed, (total erosion score > 40). *[Henceforth the term extensive erosion will be used to signify such sites with a total erosion score of >40].* This represents a channel length of just 26.5km of the 149km total surveyed (or just 18%). All of these sites occur within 7 key areas or 'macro-reaches' (defined below). This suggests that sediment sources are 'clumped' within the catchment, and that at a basic level, moving through the catchment the sediment supply system may be viewed as a 'binary' process, sources are either 'switched-on' and the area is 'active', on they are largely 'switched-off' and the area in 'in-active'. This concept of active and inactive watercourse reaches is one that has been presented in the Shelf Brook case study (a small-sized catchment in a U.K. context), and it is again shown to be pertenant in this case study at a larger scale.

As raised in Section 4.6 above, this analysis is dependant on the premise that all recorded erosion sites, are supplying fine sediments to the upper Mersey system. This is clearly a simplification of reality, and indeed the proforma records bank material type at sites of different erosion type using a four category system, (adapted from that originally developed by the RHS methodology, Environment Agency 1997), of clay/silt, sand/gravel, cobble/boulder and bedrock. However, Figure 4.8 below shows that 75% of all recorded erosion observations in the upper Mersey catchment area are occurring in bank materials that are predominately fine sediment, or contain a high proportion of fine sediment (i.e. clay/silt or gravel/sand materials). Of the remaining 25% only approx. 4% are on bedrock, the erosion of which would yield little or no fine sediments. The remaining 21% of cobble/boulder material is largely attributable to upland reaches such as the Shelf Brook, where bank materials comprise ancient alluvial deposits and glacial drift, which despite the implied predomination of coarse material, frequently has in addition significant quantities of fines, (as identified in the Shelf Brook case study).

The flood defence sediment problem at the focus site is a fine sediment problem, as detailed above in Section 4.1.2. Therefore while the presentation of erosion generically across the catchment may mask some local variability, it is adequate broadly to describe the sources of fine sediment that form the flood defence problem at the focus site, i.e. to identify the 'macro-reaches' described below.

Figure 4-8: Percentages of Different Bank Materials and Deposition Materials Recorded at all Sites of Erosion



The concept that any site in the catchment is equally likely to contribute fine sediment to the accretion problem at the focus site implies that fine material has 'an infinite transport step'. In other words that it may be transported over any distance within the catchment during a single spate event. While this is a simplification of the complex processes that govern sediment transport in any catchment, the Shelf Brook case study established that it was not an unreasonable assumption in a relatively high-energy catchment such as the upper Mersey, at least for particles of sand size and finer (which form the accretion load at the focus site).

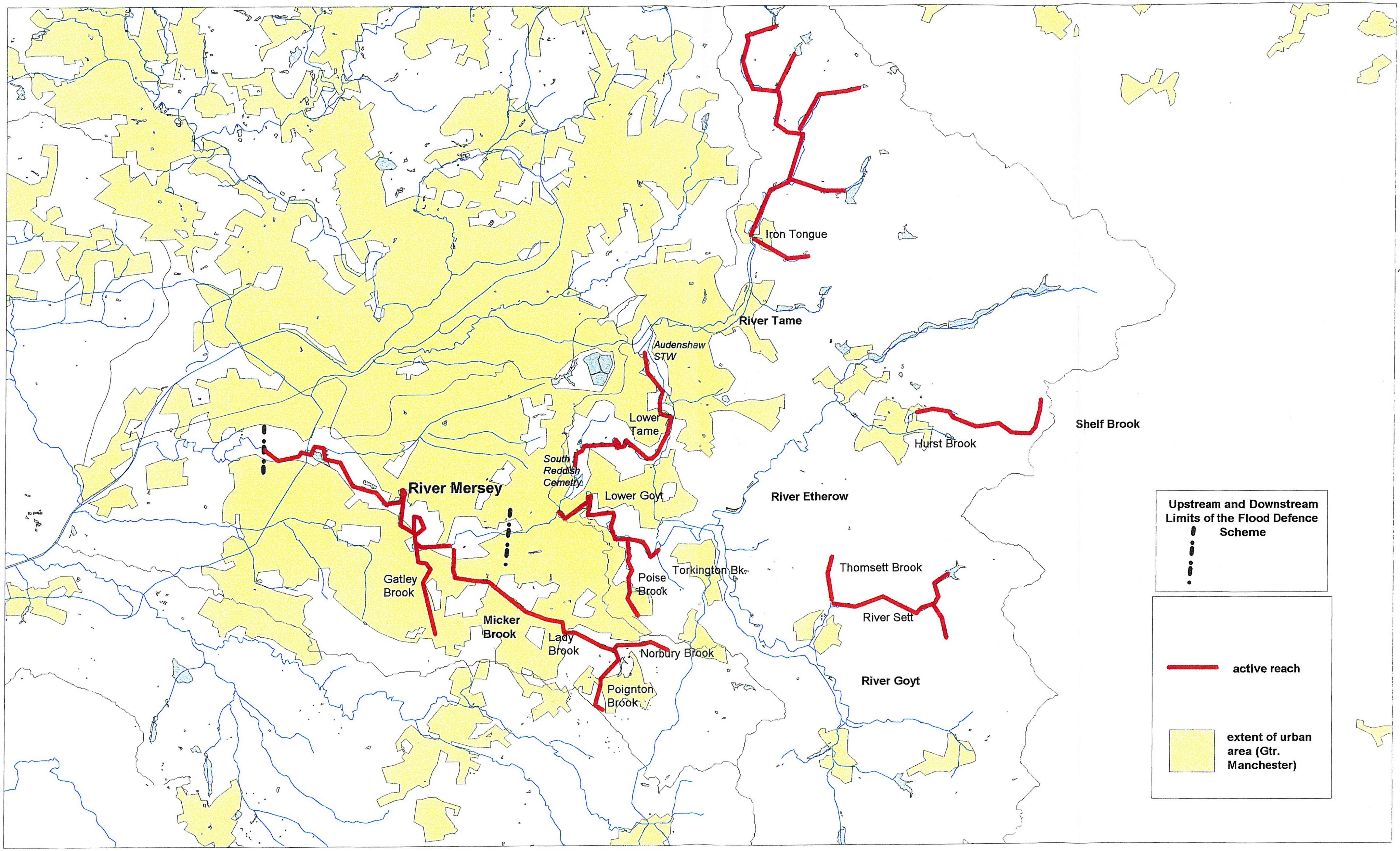
The following 7 areas (named in Table 4.9 below) may therefore be defined as active reaches (major sediment source areas). These areas are illustrated in Figure 4.9, and in the photos in Case Appendix 2 (Section 4.10).

Table 4-9: Locations of Active Reaches in the Upper Mersey Catchment

Active reach	Upstream extent	Downstream extent	Tributaries included
Upper Tame	Upstream extent of observations	Confluence with Iron Tongue	Iron Tongue
Shelf Brook (upper Etherow sub-catchment)	Upstream extent of observations	Confluence with Hurst Brook	
The Sett (minor source)	Upstream extent of observations	Confluence with Thomsett Brook	Thomsett Brook
Lower Goyt	Confluence with Torkington Brook	Confluence with Mersey	Poise Brook
Micker Brook	Upstream extent of observations	Confluence with Mersey	Poignton, Lady and Norbury Brooks
Lower Tame	Audenshaw STW (SD 975 013)	South Reddish Cemetry (SD 929 973)	
The Mersey (focus area)	Confluence with Micker Brook	Downstream extent of observations	Gatley Brook

This pattern of 'clumped' distribution of sediment source areas is likely to be related to changes in stream energy characteristics at the catchment scale.

Figure 4-9: Macro-reaches of Sediment Sources and Sinks in the upper Mersey Catchment



4.7.1.2 Deposition in the catchment

On the whole, patterns of the distribution of sites of extensive deposition (scores in excess of 40) can be seen to mirror patterns of erosion quite closely, (see Figure 4.5). In fact of the 298 sites surveyed only 5 fall outside of the active reaches identified in the consideration of sediment sources above. Of the 5 exceptions, 3 are at the confluences of similar sized watercourses, (Black Brook and Chapel Millton Brook, at SK 085815; the Sett and the Goyt at SK 002 853; the Etherow and the Glossop Brook at SK 010 953). Such sites are hydraulically prone to deposition. The remaining two sites are on the Tame at SD975013 and SD929973, these are sites of very high local sinuosity (the 500m site lengths each contain three full meanders whereas other sites within this reach contain typically one or at most two). This makes them hydraulically prone to deposition particularly in the form of point bars, which form the predominant deposit type at each site.

However from Figure 4.8 above it can be seen that, of the recorded occurrences of deposition in the catchment 91.6% are 'predominately gravel or cobble', with the remaining 9.4% of 'fines-dominated deposition features' (sands and silts) limited mostly to berm deposits, which occur predominantly in reaches where the channel has been engineering and is over-wide, with occasional fine bars upstream of major channel structures such as large weirs. So while there will certainly be some fines temporarily locked up in deposition sinks within the catchment upstream of the focus reach, even where coarse materials predominate, there is a case to support the simple premise that erosion of fine sediments as identified above in active reaches in the catchment, equates fairly directly to fine sediment delivery to the focus reach.

Within active reaches the relation of deposition patterns to erosion patterns varies somewhat. Although extensive deposition in general (>98%) occurs within the same active reaches as extensive erosion, the distribution of that deposition varies. For instance in the case of the Micker Brook the majority of extensive deposition occurs at the same sites as extensive erosion in the upper sites of the reach. Little deposition was noted in the Lower Tame, Mersey and Lower Goyt macro reaches, although this is almost certainly attributable to the history of dredging for flood defence purposes throughout much of these areas. While in the case of the Upper Tame and Shelf Brook reaches some deposition occurs with erosion at the upper sites, but there are also significant deposits towards the lower ends of the reaches, where less erosion occurs. This may be the result of local river energy characteristics, which act to regularly transfer some of the sediments over relatively short distances within the reaches.

The synergy between the distribution of active reaches of erosion and deposition means that it is valid to propose a macro-scale reach classification for geomorphological activity in the upper Mersey catchment. Such a classification may identify simply active and inactive reaches, or 'zones of production and storage' and zones of 'sediment-transfer'. This form of classification is a 'binary' classification in which 'active reaches' contain both significant erosion and deposition, and 'inactive reaches' contain neither significant erosion nor deposition. This macro-reach classification is perhaps the simplest level at which the information that has been collected and processed for this catchment can be presented to address the stated flood defence management objective of identify key reaches of sediment production. The distribution of such 'macro-reaches' is shown in Figure 4.9.

As mentioned above, despite the generally coarser nature of deposited sediments, it is likely that there are still substantial quantities of fine sediments included in the gravel and cobble bars of the catchment, and such fine material is unlikely to progress rapidly to the focus area of this study under anything apart from spate conditions when the coarser elements of such deposits are also disturbed. Therefore from a sediment management perspective the conclusion may be drawn that it is wise to concentrate on the control of sources in the lower catchment first to best affect a reduction in the yield of fine sediment at the focus site. (This will be discussed in more detail in Section 4.7.6 below).

4.7.2 Causes of erosion and deposition

Tables 4.7 and 4.8 address one of the key geomorphological objectives of this case study, 'to gather data on the causal factors behind the observed patterns of erosion and deposition in the study catchment'. Table 4.7 appears to illustrate that the majority of erosion within the upper Mersey catchment is attributable to 'no obvious immediate artificial cause', however the consideration of this category must be tempered by acknowledging that long-term changes in catchment landuse patterns have occurred. Therefore much of this erosion cannot be considered truly 'natural' as the natural condition of the catchment is one of mixed woodland extending to the bank top (the prehistoric 'wildwood'). Under truly natural conditions sediment-yields would be at a fraction of their current levels.

Of the 'artificial' causes expressed in the Table 4.7 above, the significance of footpaths is surprisingly prevalent, this is a reflection of the degree of urban development in the wider area and the extent of bankside access. Footpaths contribute directly to erosion by providing areas of unvegetated, often disturbed ground surface, which delivers sediment to the channel through rain-wash processes or directly if the water level of the river covers such paths under spate. Footpaths, in common with poaching, may also physically break down a riverbank if heavily used, again directly inputting sediments.

The figure for poaching is lower than expected, given the prevalence of both rough pasture (present at 69% of sites) and stocked improved grassland (present at 44% of sites). Though it should be noted that stock may significantly contribute to erosion in other areas, if only by retarding the development of mature bank vegetation, even if their presence is not immediately evident.

The effects attributable to hydraulic changes (effects of structures such as weirs, bridges, culverts etc), deflection (effects of in-channel deflectors), urban activities (e.g. fly-tipping, building / garden waste etc), and vegetation management are all moderate, and where present are associated with a catchment containing large areas of urbanisation.

4.7.3 Types of erosion and the scales at which they occur

The consideration of erosion types, like the consideration of 'causes' discussed above, addresses the geomorphological objective that is expressed in Section 4.4, to increase the understanding of the different mechanisms producing erosion. This will provide useful information to inform the management of catchment sediment sources (discussed below). The individual erosion types recorded in the geomorphological audit will now be discussed individually below, photos illustrating the different types are shown in Case Appendix 1.

Eroding Cliff (E1) - This is the most common form of erosion, it tends to occur in larger quantities as meso or macro features. It may result from fluvial action, the operation of freeze-thaw processes, pore-water differential affects, or artificial influences, (such as those outlined in 4.7.2 above).

Stable Cliff (E2) - This is a less common feature, tending to occur at the macro scale, probably a result of the affects of flood waters eroding large areas of secondary sites of erodibility (e.g. banks at extreme downstream end of meanders); they then stabilise under normal flow conditions. Such sites are stable in so far as they were well vegetated at the time of the audit, however they have been active sediment inputs and they have the potential to be reactivated under spate flow conditions.

Slump (E3) - Tending to occur as meso / macro features, this form of erosion is attributable to wider-spread bank failures resulting from unstable ground conditions. It includes planar failures in non-cohesive laminar bank substrates, and rotation failures in cohesive material.

Toe Scour (E4) - This is the third most commonly occurring form of erosion it tends to occur at the medium scale. This is because it tends to be produced by more localised processes, and because extensive development of an undercut eroding toe is likely to promote upper bank collapse, (therefore changing the erosion type to Eroding Cliff). It is produced by the same processes as eroding cliff erosion.

Creep (E5a) - This is the watercourse input of sediments from downslope colluvial processes, i.e. the migration of saturated soils etc. on steep slopes under the influence of gravity, producing a 'corrugated' effect at the ground surface. It is very uncommon, occurring only in areas with high, unstable, steeply sloping banks.

Slide (E5b) - A more rapid and deeper-seated version of creep, this involves the transit slabs of slabs of ground material down steep slopes under gravity, in an extreme form it may constitute a land slide. This form of erosion is rare for the same reasons.

Wash (E5c) - The second most common form of erosion, this is attributable to direct fine sediment input from the floodplain. Such erosion tends to occur in areas of suburban landuse or areas of tracks and road as a result of input from derelict land / wasteland and road silt, and also in areas of rough pasture and grazed improved pasture as a result of over grazing producing areas of bare ground. This is shown in Figure 4.10 below, in which the distribution by landuse is shown where wash erosion is recorded as present or extensive (percentage of reaches), and compared to the distribution by

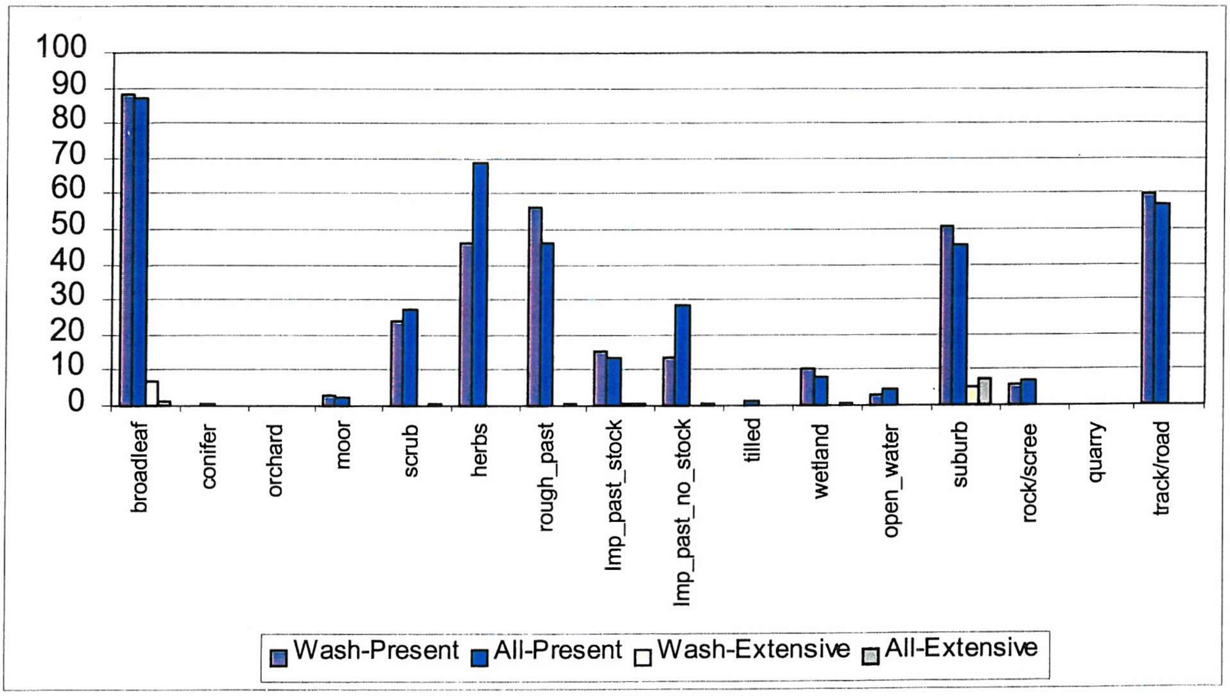


Figure 4-10: Occurrence of Wash Erosion by Landuse in the Upper Mersey Catchment

landuse across all reaches (percentage of reaches). From this figure it is also possible to deduce that wash erosion is notably less likely on landuses containing high or dense vegetation such as tall herbs and improved grassland with no stock.

Bed Scour (E6) - This is very uncommon, it is specific to natural areas below steps and waterfalls and areas of channel subject to the affects of artificial features, such as points immediately downstream of weirs, or areas between bridge arches. It may be the case that the location of such erosion (at the river bed) means that it is by nature harder to observe than bank erosion processes, and thus its presence may be under-recorded.

4.7.4 The experimental use of different sampling strategies

The identification of the extent of active reaches in the catchment is a big step in the process of holistic sediment management. However, a key question which must first be asked is: "would it have been possible to identify the same active reaches using a lower frequency of survey", e.g. surveying only half or a quarter of the sites, and thus making substantial time and cost savings? This question seeks to address the geomorphological objective of this study developed from the Shelf Brook case study (expressed in Section 4.4) to test whether it is possible to produce the same audit findings from a reduced survey coverage. A second methodological question is also pertinent at this juncture, that is: "would it have been possible to have identified the same active reaches using a simpler from of survey", such as 'a simple classification approach', which is less time consuming, and therefore may be more cost-effective, to perform? Finally, from a purely methodological point of view a third question arises, that is: "would the same active reaches have been identified using other forms of existing catchment survey techniques, e.g. River Habitat Survey"? This final question is again pertinent with reference to the global objectives of developing the geomorphological audit, in that they compare the performance of the audit to an existing method of geomorphological practice.

The summary Table 4.10 below provides an insight into these and other questions. The distribution of extensive sites of erosion produced by the different strategies can be seen in Figures 4.11 to 4.14 and 4.16 – 4.17.

Table 4-10: Comparison of the Occurrence of Extensive Erosion by Active Reach and Sampling Strategy

% of all sites found in each active reach	Total Catchment	1. Upper Tame	2. Shelf Brook	3. The Sett	4. Lower Goyt	5. Micker Brook	6. Lower Tame	7. Mersey focus area
	298 sites	15.4	4.7	5.7	6.0	5.0	5.4	10.7

Sampling Method	Sample size		Distribution of total observations of extensive erosion by active reach						
	% of sites with extensive erosion	No. of Sites	1. Upper Tame (%)	2. Shelf Brook (%)	3. The Sett (%)	4. Lower Goyt (%)	5. Micker Brook (%)	6. Lower Tame (%)	7. Mersey focus area (%)
Continuous	18.8	53 sites	18.9	13.2	3.8	7.5	26.4	17	13.2
50% interval	15.3	25 sites	20	12	0	8	28	16	16
50% random	20.9	14 sites	7.1	14.3	0	14.3	28.6	14.3	21.4
25% interval	15.3	25 sites	24	12	4	12	20	12	16
25% random	20.9	14 sites	14.3	14.3	0	7.1	21.4	28.6	14.3
RHS	21.4	12 sites	8.3	8.3	0	16.8	25	25	8.3
Simple classification	14.1	42 sites	19.1	16.6	4.8	2.4	35.7	0	16.6

The upper part of Table 4.10 above shows the percentage of all sites found in each reach, this gives a comparison between the sizes of the reaches relative to one another. For example, the largest active area is the Upper Tame which contains 15.4% of all surveyed sites (46 sites), while the Shelf Brook is the smallest reach containing just 4.7% (or 14 sites).

Figure 4-11: Sites of Active Erosion in the Upper Mersey Catchment (50% interval sample)

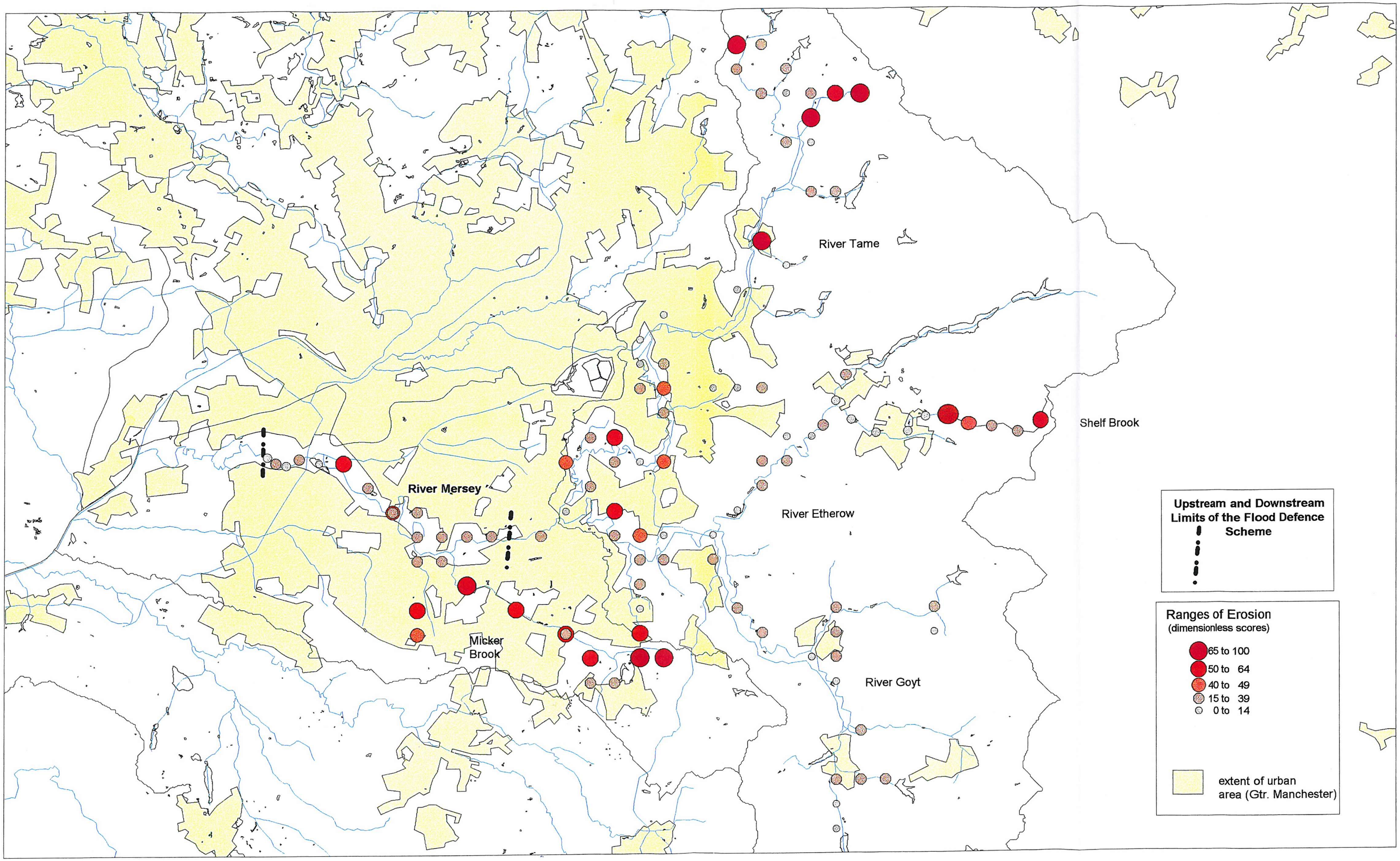


Figure 4-12: Sites of Active Erosion in the Upper Mersey Catchment (25% interval sample)

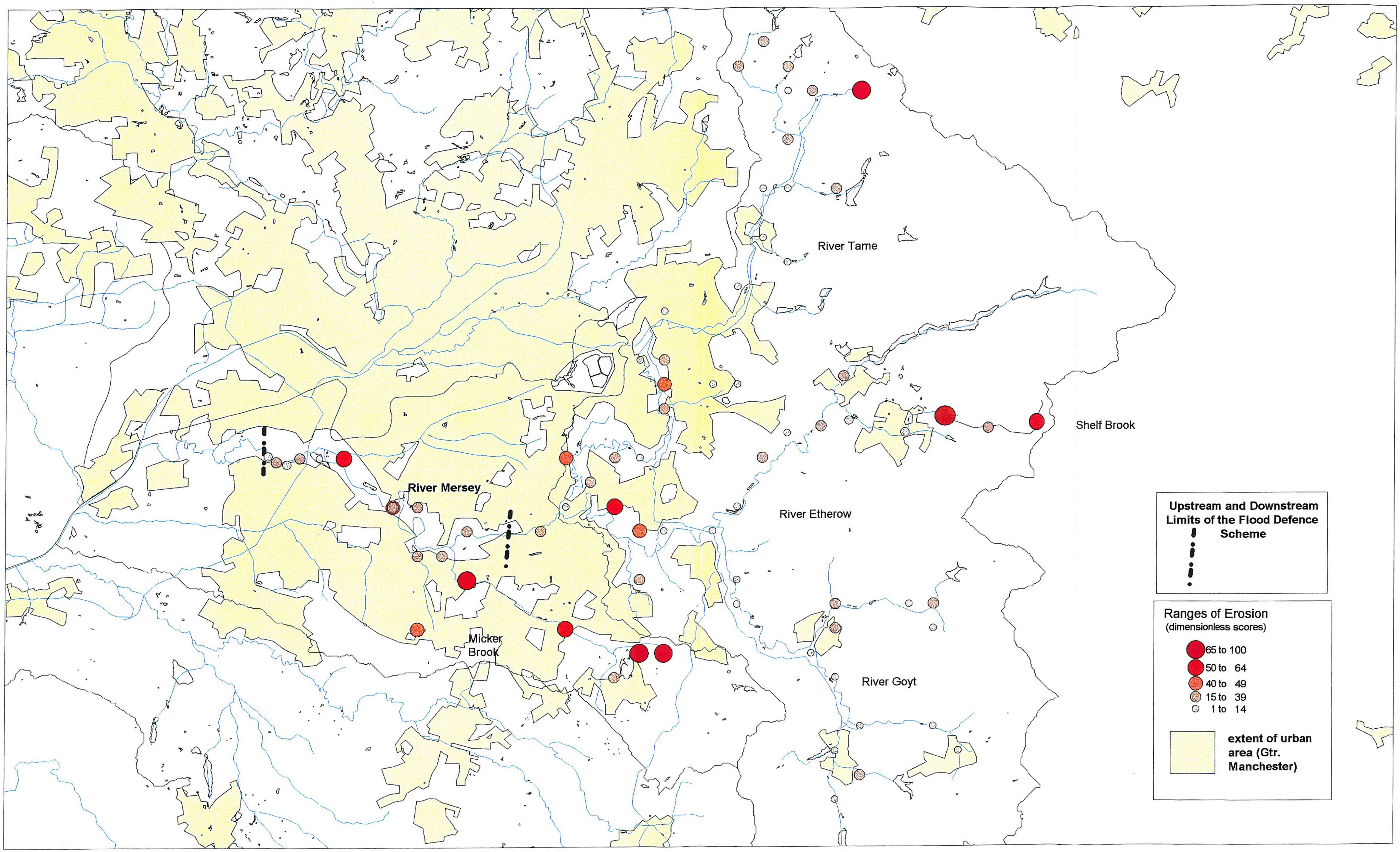


Figure 4-13: Sites of Active Erosion in the Upper Mersey Catchment (50% random sample)

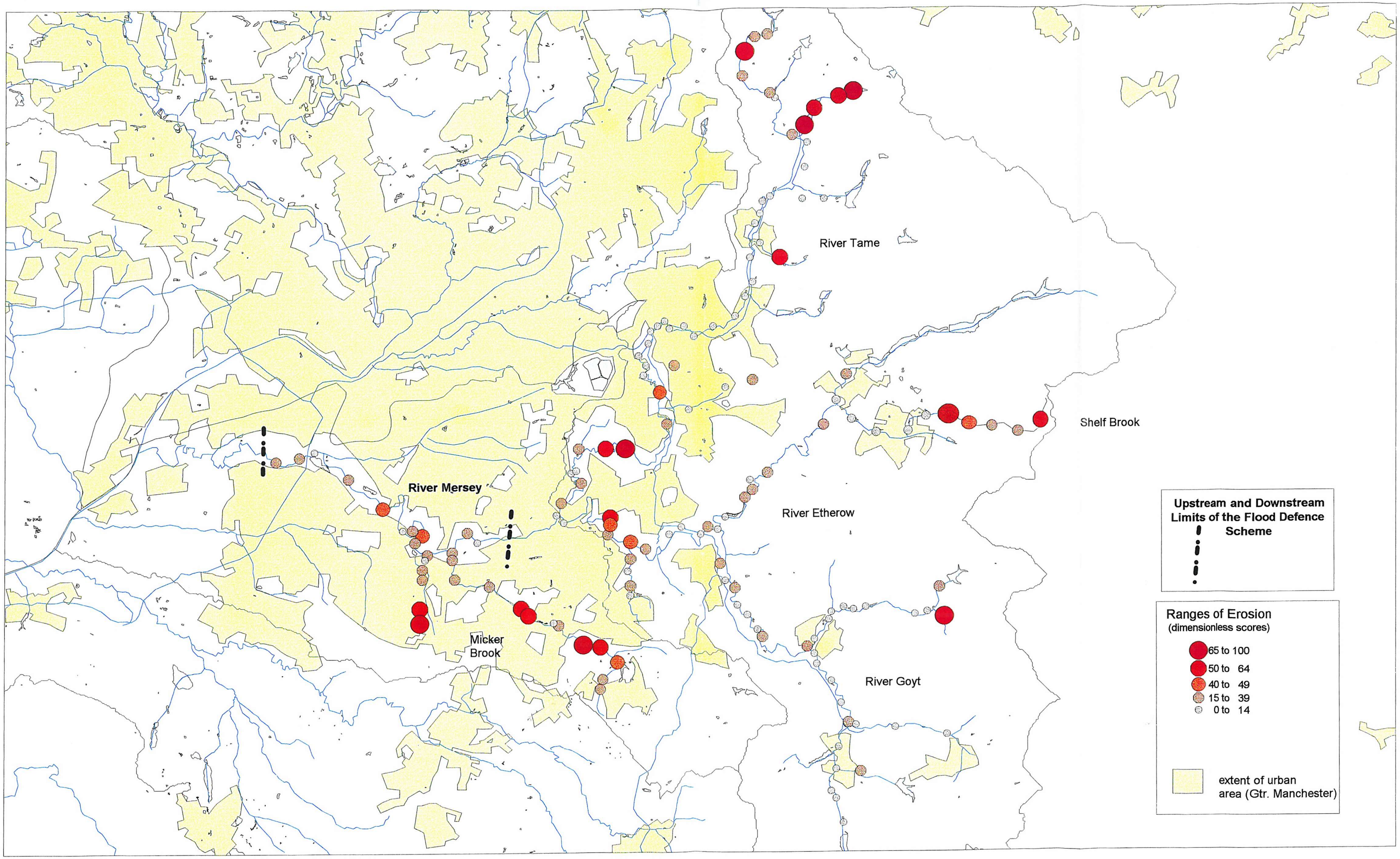
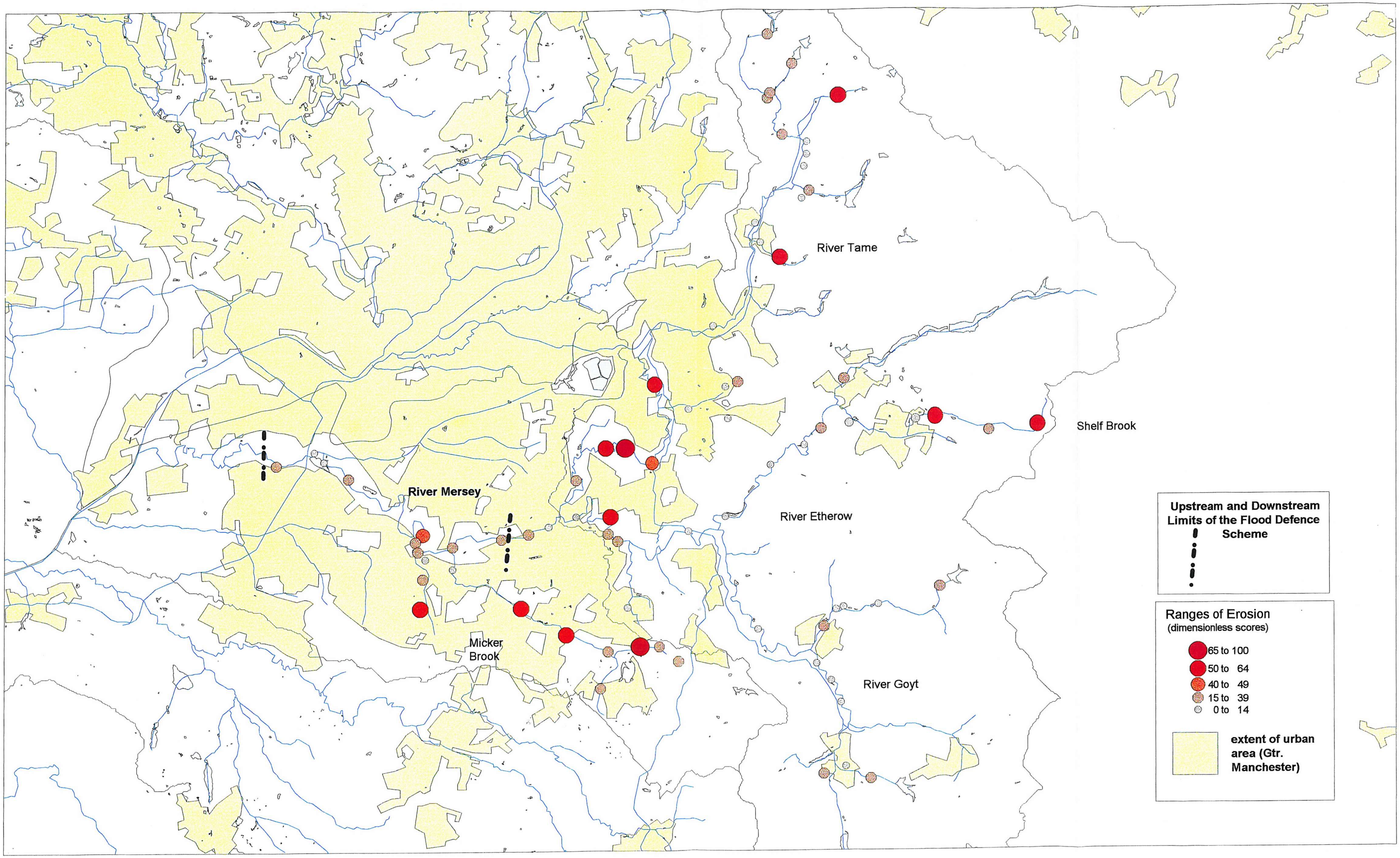


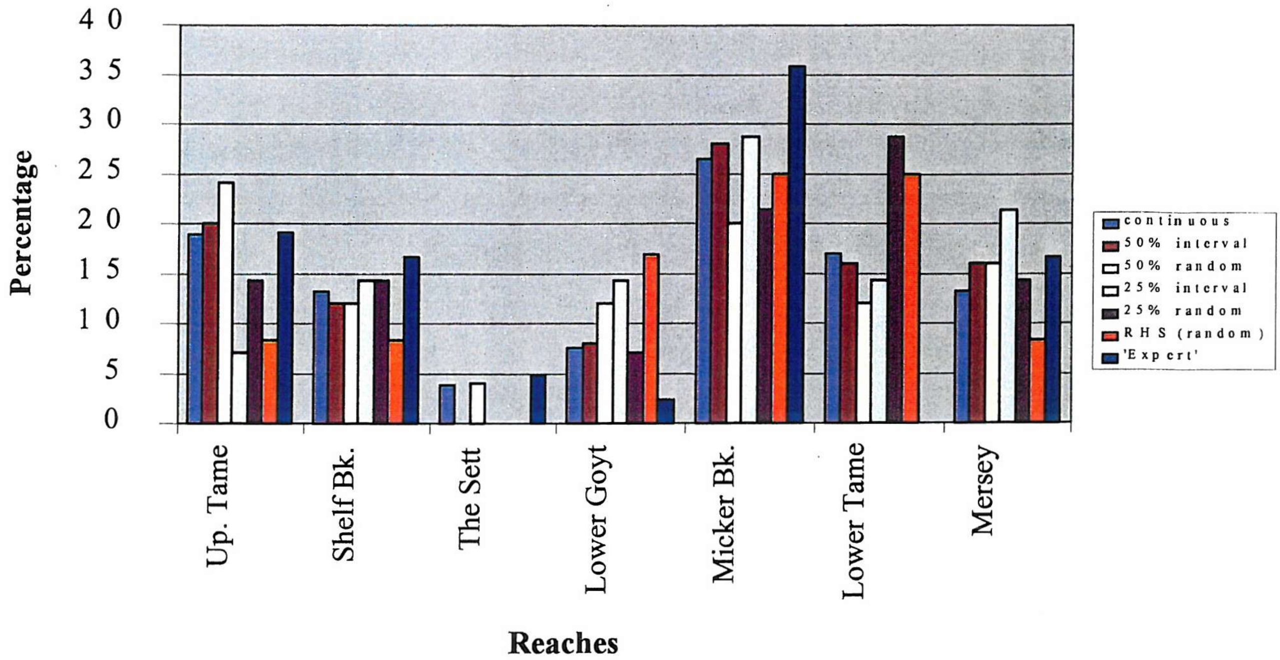
Figure 4-14: Sites of Active Erosion in the Upper Mersey Catchment (25% random sample)



The lower part of Table 4.10 shows the distribution of the total population of sites of extensive erosion, across the 7 active reaches, by percentage, under different sampling strategies. Therefore the continuous results (top line) give the most precise expression of distribution, as they are taken from the total population of extensive erosion sites. This shows that the Micker Brook makes up only 5% of the catchment watercourse length, (percentage taken from the top part of the table), but it accounts for more than 25% of the observations of extensive erosion. The next largest sources are the Upper and Lower Tame, followed by the Shelf Brook and the Lower Goyt. The Sett is a marginal source area only.

The first point of note concerning the 50% and 25% sampling frequency datasets, (reduced frequency methods), is that interval and random sampling at both frequencies produce exactly the same population sizes of extensive sites (25 and 14 respectively). In terms of the distribution of sites across the active areas, for all four reduced-frequency methods the general trend appears to be similar, Micker Brook and the Tame sites consistently appear as the most active reaches, and the Sett appears constantly as a marginal source. The RHS and 'simple classification' samples are not from the same root population as the reduced frequency methods (i.e. the continuous dataset). The derivation of the 'extensive erosion' sites from the RHS data are discuss in Section 4.6 above, while 'extensive erosion' was derived from the simple classification dataset simply by taking the sites classified in the audit entry 'overall impression' as 'extensive'. Therefore the different sample sizes of extensive erosion sites that they produce in column three are to be expected. However, in general terms these techniques too suggest a similar distribution of extensive erosion across the active reaches. A summary of the distribution of extensive erosion by active reaches is shown graphically in Figure 4.15. To test the significance of the similarities between the distributions, and thus answer the questions pertaining to lower frequency, simpler or alternative surveying methods (raised at the beginning of this sub-section), it is necessary to employ statistical means.

Figure 4-15: Distribution of Total Observations of 'Extensive Erosion' by Macro-



The datasets were compared using contingency tables, in which the continuous survey formed the control dataset and the other methods formed a series of experimental datasets. The chi-square test was adopted to perform these comparisons, using the statistical package MINITAB (release 12.21). The null hypothesis is that the experimental dataset and the control are drawn from different populations, and the alternative hypothesis is that the experimental and control datasets are both drawn from the same populations. Table 4.11 below gives a summary of the findings produced, the full analysis forms Case Appendix 3, (Section 4.11).

Table 4-11: Statistical Comparison of all Sampling Methods Using Chi-Squared Tests (Summary Data)

Survey Frequency	Method	Significance level at which control and experimental datasets found to be from same population
50%	Interval	99%
50%	Random	88%
25%	Interval	50%
25%	Random	73%
Approx. 25%	RHS (random)	51%
Continuous	Simple classification	13%

In order to undertake this analysis the results from the Sett reach had to be combined with the Lower Goyt results, this was because the occurrence of zero values seriously biases the chi-squared analysis tending to make the results invalid. This combination approach is reasonable as the Sett is part of the wider Goyt system, and is in any case a very marginal source area.

The results suggest that it is practical to adopt a 50% survey frequency, and define the same relative distribution of extensive erosion between active reaches, as a continuous sample. The interval method is shown to be the most reliable method of sampling to achieve this. At a 25% frequency there is shown to be a significant decrease that the likelihood of the data produced will be significantly representative of the distribution of extensive erosion across the whole population, (ie. the full catchment watercourse network).

Therefore these findings suggest that for geomorphological audits of large catchments (e.g. in excess of 500 square kilometres), it is worth investigating the cost-benefit of surveying only a 50% interval sample of the full watercourse network. Although this assumes that erosion and deposition are lumped in a similar way to the upper Mersey catchment, and an initial rapid 'walk-over survey' or a Catchment Baseline Survey might initially be performed to assess this prior to the audit, (i.e. observations at a range of sites easily accessible sites, ideally close to roads, throughout the catchment).

The RHS data are shown to give a similar relative distribution of extensive erosion as the geomorphological audit technique designed for this case study at equivalent survey frequencies (25%). It does however give consistently higher estimates of erosion (as shown in Figure 4.17). It is also less practical to consider a higher-frequency application of the RHS technique across a catchment of this size, due to reasons of time and cost.

The simple classification approach was found to produce results that bore little statistically-significant comparison to the quantified data of the continuous total erosion scores method. As was the case in the Shelf Brook case study, this therefore suggests that it is difficult even for the trained, experienced observer to reliably summarise the scale of geomorphological processes occurring over several hundred metres of watercourse quickly by eye, without a detailed continuous consideration of that site. The credentials of 'training and experience' of the consultants undertaking the data collection was established prior to letting the audit contract, and the consultants provided geomorphological credentials that would be acceptable under the requirements of the Environment Agency *National contract for engineering and environmental services*, (Environment Agency, 2000b), (written by the author) now taken as a Northwest regional standard for procuring geomorphological services.

Figure 4-16: Simple classification of Erosion Sources

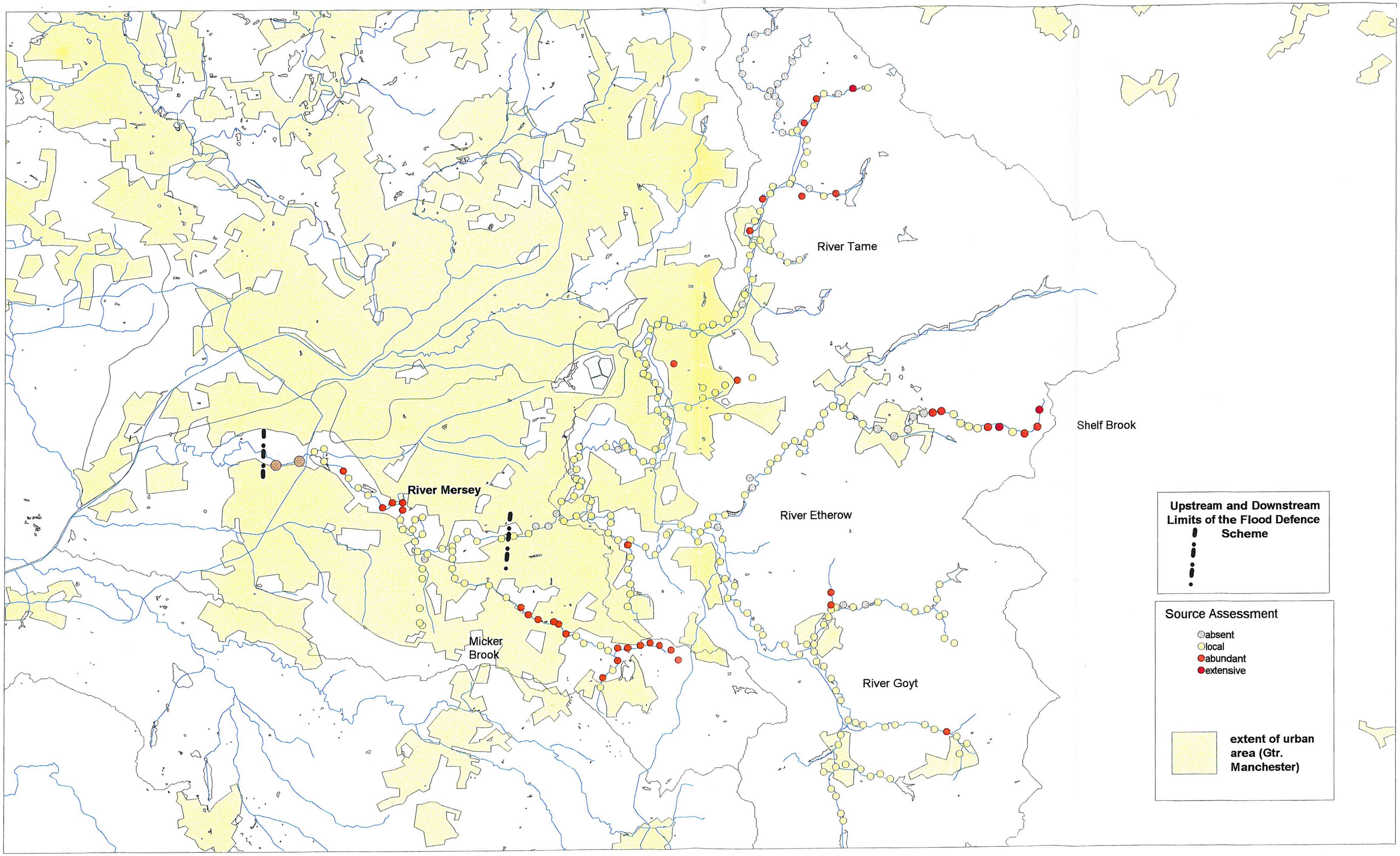
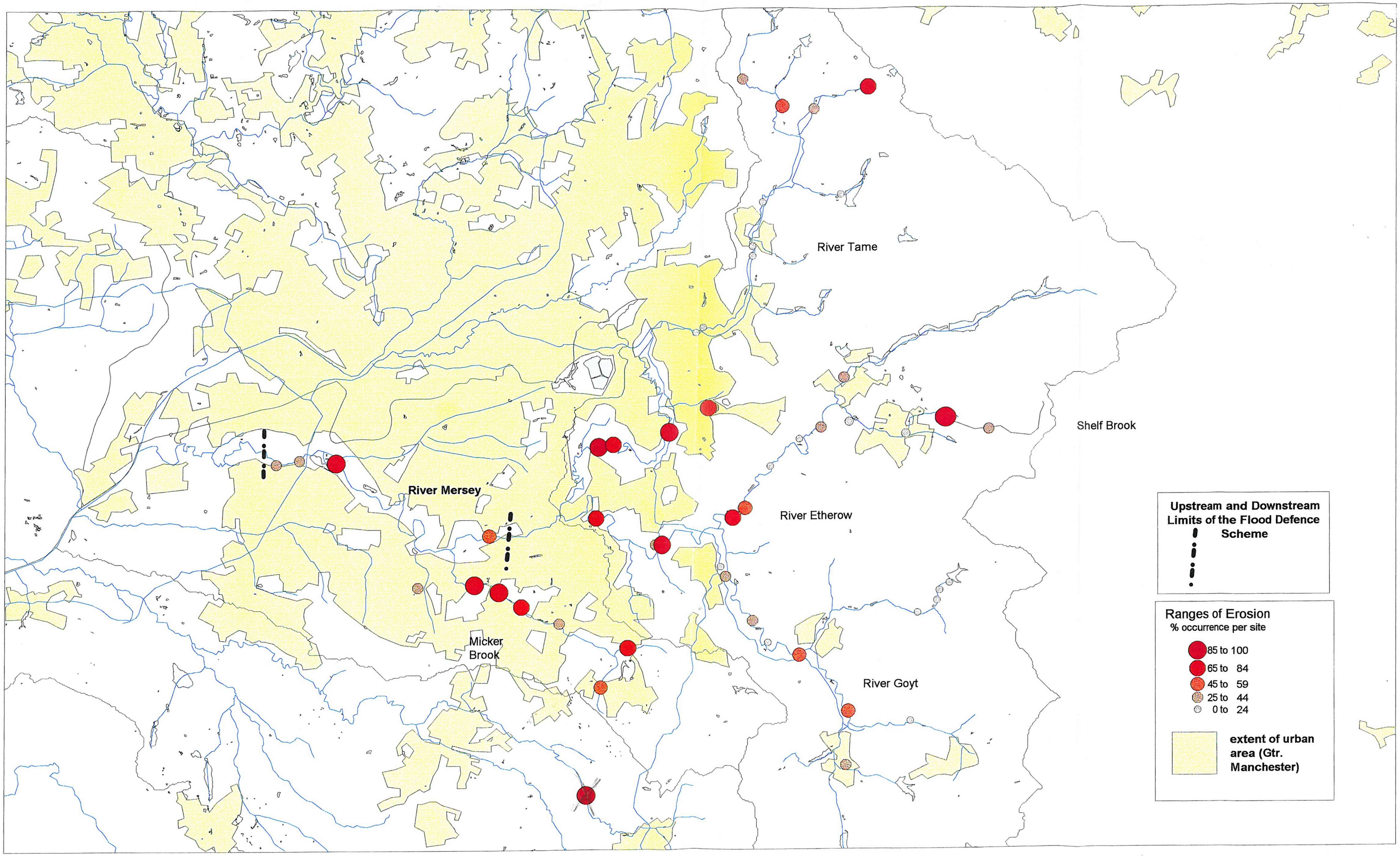


Figure 4-17: Sites of Active Erosion in the Upper Mersey Catchment (25% random RHS sample)



4.7.5 Replicability of the survey methods used

In order to assess the replicability of the findings using the audit proforma designed for this study, a sub-sample of 10 sites originally surveyed under contract by the consultants was resurveyed by the author. Sites were selected on a random basis across the catchment. A comparison between the original survey and the re-survey data were then undertaken. The results in Table 4.12 were obtained.

Table 4-12: Comparison of Variation Between Original Survey and Resurvey Results for Selected Upper Mersey Reaches

Type of observation (see survey proforma and keynotes (Figure 4.2) for definitions	Difference in recorded observations
Total erosion scores (as devised in sect. 5.1)	Max. +/- 30%
Substrate condition	15% of observations differ
Engineering	20% of observations differ
Total deposition scores (as devised in sect. 5.1)	Max. +/- 30%
Floodplain Landuse	5% of observations differ for extensive 20% differ for present
Flood Protection	10% of observations differ
Floodplain Wetlands	10% of observations differ
Other Features (Tributaries)	Meso & Macro = 10% of observations differ Micro = 50% of observations differ
Overall Impression	35% of observations differ

The results show good consistency between the observation of flood protection, wetland and extensive landuse features. All such features are fairly large scale, and in the case of wetlands relatively rare. The differences in substrate condition are minor and are likely to be attributable to substrates which are near the boundary of their class, e.g. large gravels that may be interpreted as cobbles. The moderate differences in present (minor) landuses are probably attributable to the scale of occurrence in the case of the latter (i.e. just 1% or 5 metres of banktop needs to be covered to be recorded). In the case of engineering features, moderate differences are probably attributable to the fact that certain types of works such as reinforcement and resectioning can be overgrown and difficult to spot, particularly under conditions of poor survey visibility.

Tributaries exemplify a specific survey problem, they are generally consistently observed and classified at meso and macro scales, but at the micro-scale (under 1 metre) there is a lot of variation. This is likely to be caused not only by such features being small and difficult to spot in the field, but also by some such features simply not being present under survey conditions which followed a period of dry weather. The value of +/- 30% for total erosion and deposition is attributable to two major themes of variation. One is the consideration of scale, i.e. where the same feature has been recorded as meso instead of macro or vice-versa. This is probably due to variations in water-level at the times of survey and resurvey leading to the observations of different surface areas, and also differences in definition as to the exact location at which a bank toe or a bar edge begins or ends. A second consistent source of error was the inclusion / exclusion or observations of bank toe erosion, in fact such discrepancies amounted for nearly 50% of the differences in erosion observations. These differences are likely to be solely attributable to variable water level at the time of survey obscuring or revealing the features.

The marked differences in overall impressions is again testament to the difficulty of summarising geomorphological processes over any significant length of watercourse in a single subjective statement.

Overall this limited repeat survey test of the replicability of these survey methods yields several important findings:

- Variability may ensue under conditions of poor visibility, (rain, darkness etc.), and surveys should not be undertaken under such circumstances.
- Variable water levels may also lead to inconsistent results, and the adoption of a general survey guideline that no observations are made under conditions of greater than median water level at a named permanent gauging station, may for instance be required.
- Overall the variations observed are relatively minor. Any observation-based survey

methodology is going to be prone to some degree of variance in results from inter-surveyor interpretation, indeed the RHS has established that such 'operator errors' are inevitable in the collection of large quantities of field data over a sizeable area, (Environment Agency, 1997). However, confidence limits of +/- 30% are acceptable, and with the prospect that by addressing the above two points, and some other slight adjustments to the proforma used in this case study (discussed in chapter 5), substantial improvements in performance could be achieved.

This consideration of inter-surveyor variability and thus replicability of the audit methods represents a successful effort to address another aspect of the geomorphological objectives of this case study, (as expressed in Section 4.4).

4.7.6 Management implications

The management implications of this case study amount to the demonstrable 'tangible benefits' of the geomorphological audit, and as such they seek to address another of the geomorphological objectives as defined in Section 4.4. From the sections above it can clearly be seen that using the methodology developed in this case study it is possible to identify not only 'where in the catchment are the major sediment sources', but also 'what types of erosion are present, and in what proportions'. In addition to identifying 'what are the locations and causes of artificially enhanced erosion'. However, despite the academic interest of such observations, the question must be asked, 'what are the implications from a management point of view'?

Possible actions to reduce / manage sediment-yields:
There are a variety of management options that will help to increase the efficiency of sediment management in the upper Mersey catchment, and thus reduce current maintenance costs. Such techniques fall into 2 areas:

1. Reduce the production of fine sediments at source.
2. Interrupt and manage the transport of sediment.

The cost benefit of these options should be considered, as there is a high annual spend on heavy maintenance indicated in Table 4.1 above, (i.e. approx. £70,000). For example a reduced workload resulting from a reduction in sediment-yield of just 20% could result in a cost saving of £175,000 over just 10 years (at 1998 prices).

4.7.6.1 Control of sediment inputs at source

This is the most sustainable long-term way in which to reduce sediment-yields and it should be undertaken on a site-by-site basis. It is suggested that the 33 sites in the four areas of erosion at, feeding into, or closely upstream of the focus area identified in Section 4.7.1 above, (i.e. Lower Goyt, Micker Brook, Lower Tame, the Mersey [in the focus area] and its minor tributaries), are targeted for bank rehabilitation works that will serve to reduce sediment-yields.

The data collected by this project can supply details as to the causes and types of erosion present at each sites, and then the following comments on artificial causes and management techniques for different types of erosion (in Table 4.13 below), should be considered in designing appropriate rehabilitation packages on a site by site basis. However, it should be considered that erosion is to a greater or lesser degree a natural geomorphological process within the catchment context, and it is a necessary part of the physical change within a river system that feeds habitat development and diversity. Therefore efforts should be made to target identified areas of accelerated erosion in the first instance. The database developed as part of this case study could be used to inform managers as to the location of such areas with the key macro-reaches identified. In addressing bank erosion and sediment source creation there is however always the potential risk of some adverse ecological impact, however given the need to continue providing flood defence the alternative to treating maintenance problems at source in this way is the continuation of dredging in the focus site, and the ecological impacts of this work are in themselves very detrimental. Where the potential impacts of physical work to banks are greatest, additional methods may be used to assess and minimise the effects of such actions. An example of this might be undertaking of a Bank Assessment Record Sheet, (the Universities of Southampton, Newcastle and Nottingham 1997), or the methods of bank assessment described in the Waterway Bank Protection Guide, (Environment Agency 1999b).

Artificial Causes:

- Damage from footpaths - Where the problem is direct input of fine sediment from broken footpath surface, some form of artificial surfacing such as bark chipping or pitching may be considered. However where the pressure of footpath use has caused a failure in the structure of the riverbank the possibilities of moving the right of way back from the riverbank should be investigated. Where this is not an option more substantial engineering methods may be required, (e.g. rip-rap, gabions, etc.), (Hey and Heritage, 1993).
- Poaching - The introduction or repair of stock-proof fencing should be investigated, (this should also be undertaken in conjunction with any planting work undertaken in grazed areas). An initial assessment of stock densities would also be useful to target such efforts.
- Hydraulic Change - Related erosion might be eased by the introduction of works to train velocity currents away from eroding banks.
- Urban Activities - Fines resulting from such sources may be addressed by clearing debris and refuse from riverbanks and making access harder to prevent future tipping.
- Vegetation Management and Deflection are not significant causes of erosion, (although they may encourage deposition upstream).

4.7.6.2 Considering the benefits of reducing sediment inputs at source

A worked example including some 'typical approximate costs' is detailed below. At 1998 prices the following costs apply: fencing = £3 per metre, willow planting = £2 square metres, grass seeding = £0.30 sq. m, bank re-profiling = £11 cubic metre (for works and disposal of spoil at 'small working sites', e.g. 20-30 cu. m)[12]. Therefore, a site with 200 sq. m erosion from eroding cliffs requiring seeding through out and the removal of 30 cubic metres spoil where re-profiling is occasionally needed, and a further 100 sq. m of bank toe erosion requiring willow planting would cost a total of £590, with a further cost of perhaps £1500 to provide 500 metres of fencing if the land adjacent to the watercourse was grazed. From this example it can be seen that with a

[12]Based on estimates given in personnel communication with Environment Agency (NW), Ecology staff.

relatively low investment, fine sediment production can be tackled at source. If a similar figure of £2000 were to be spent at each of the 25 sites of most active erosion (baring in mind that only 53 sites in total were identified as active) it would cost £50,000, (less than the £70,000 average cost of removing sediment from the focus site for a single year). It does not seem to require a great leap of faith to believe that such works would pay for themselves in less than 10 years even if they achieved only a most conservative reduction in fine sediment supply rates of 10%.

Table 4-13: Possible Management Techniques Appropriate to Reducing Sediment Inputs from Different Types of Erosion

E1 = Eroding Cliff	Seeding, planting soft or hard engineering options (depending on nature of site, see Hey and Heritage, 1993), possibly in conjunction with the reduction of bank angles by battering back.
E2 = Stable Cliff	Increase vegetation cover by seeding and/or planting.
E3 = Slump	Stabilise banks with hard engineering such as riprap or gabions, use planting and seeding (especially at upstream and downstream extent of works), in conjunction to soften and prevent outflanking.
E4 = Toe Scour	Revetment (e.g. rip-rap), or planting at toe (e.g. willow stakes).
E5a = Mass Wasting (Creep)	Planting to increase bank stability.
E5b = Mass Wasting (Slide)	Planting in conjunction with deep-seated hard engineering to consolidate banks.
E5c = Mass Wasting (Wash)	Bank top planting and seeding and exclosure to promote development of 'buffer strips'.
E6 = Bed Scour	Hard engineering at bed, (e.g. blockstone, rip-rap or gabion mattresses).

(N.B. All options involving planting or seeding in areas where banktop landuse is grazing should also be fenced.)

4.7.6.3 Action to prevent the transport of fine sediment into the focus area.

Another example of an alternative method which would serve to shut down some of the sediment sources identified above, is the construction of small scale sediment traps on the tributaries that feed directly into the focus area may produce a significant cost benefit. The premier example of this would be to site a sediment trap at the downstream extent of Micker Brook, just upstream of its confluence with the Mersey.

A trap would best take the form of a check weir with a concrete bed immediately upstream, with a hard ramp and turning circle adjacent to the structure feeding access to an existing roadway. A trap would serve to pond flows and encourage settlement of fines in a control environment from which they can be easily and quickly removed. The dimensions of such a structure should be determined by an estimate of the sediment-yield of the brook over a reasonable servicing period e.g. six months, this could be determined by the installation of a turbidity meter on the Brook for a one year monitoring period. The crest level of a check dam could be determined by modelling velocities in the trap under different levels. A critical velocity may be determined by particle size analysis of samples taken from eroding banks on the brook. Such a structure is likely to cost something in the same order as the Shelf Brook gravel trap (£20,000), which again is only a small proportion of a single years fine sediment maintenance cost in the focus reach. A cheaper method might be to plant an extensive area of reed bed as an alternative trap for fine sediments.

A final intangible benefit, is the fact that the findings of this case study are being applied to the catchment, above and beyond any works which might be undertaken as part of the flood alleviation scheme, through the Local Environment Agency Plan (LEAP). This process has been initiated by the inclusion in the Tame / Goyt / Etherow LEAP of the issue *'Sediment deposition causing increased flood risk'*. Which uses the results of this project to highlight the need to reduce fine sediment loads from the upper Mersey catchment.

4.8 Conclusions on Application of the Audit Technique to Upper Mersey

4.8.1 Summary of the performance of the audit with reference to the global objectives

This case study addresses the global geomorphological objectives of this project, and the additional objectives as defined in the conclusions of the Shelf Brook case study, (both sets of objectives are defined in Section 4.4 above). In terms of the first and second *versatility* aspects of the global objectives, this case study shows that the audit methods developed can be applied to a large catchment that is varied in its physical habitats, including small upland watercourses, large lowland systems and everything in between, with a consequently wide range of substrate sizes and other geomorphological factors. There is also a wide range of landuses in the catchment extending up to the bank crests of the watercourses, and the significance of such variety has been shown in the relative contribution of certain landuses to sediment delivery from beyond the confines of the river channel.

It has additionally been demonstrated that the audit method can be used to inform the flood defence management objectives of the Mersey flood alleviation scheme (third *versatility* objective), in other words the audit has successfully identified the main areas of sediment sources in the catchment. This case study has also shown that the audit methods can be applied at the feasibility stage of a flood defence project, (fourth *versatility* objective). In doing so it was necessary to work within tight deadlines, i.e. to collect the audit data and provide initial findings within six weeks.

The performance of the audit in respect of the first of the global *utility* objectives was addressed in some detail in the Shelf Brook case study, particularly as regards existing methods of engineering science and geomorphological science. This case study has taken the comparison to methods of geomorphological practice a step further forwards by comparing the performance of the audit methods with that of the River Habitat Survey. The RHS was chosen for this purpose, as it is the mostly widely applied data gathering method within the Environment Agency to contain a substantive proportion of geomorphological data. From this comparison it appears that the geomorphological audit is better suited to the determination of sediment sources across a catchment even at a reduced (25%) sampling intensity. Although a direct comparison with other methods of rapid catchment appraisal, (such as Catchment baseline audit), have not been made in this case study the importance of the findings concerning the causes and types of erosion recorded using the audit as concerns management implications and tangible benefits, tends to suggest that even if such methods identified sediment sources as efficiently as the geomorphological audit method developed by this project, this audit method still has advantages as concerns application to flood defence. It is also quicker, and therefore cheaper, to perform than methods such as fluvial audit or detailed bank erosion assessment, (as the more extensive proformas / methods of such techniques take longer to complete), although it should also be borne in mind that such methods may be more applicable that the geomorphological audit in the case of more complex flood defence objectives. It has also been shown that the audit methods produce a far more comprehensive assessment of active sediment sources than a simple classification based upon the instinctive impression of a field geomorphologist, this is important as if the mere quick impressions of 'experts' could deliver the same results as the audit method, then there would be no point in going to the time and expense of undertaking the audit exercise.

As anticipated, (and stated in the geomorphological objectives, Section 4.4), unlike the application of the audit methods to the Shelf Brook, it was not necessary to employ any additional data or methods to fulfil the flood defence objectives of this study, (second *utility* objective). Finally, in terms of the global *utility* objectives, the tangible benefits of using the audit approach to inform flood defence management decisions are clearly demonstrated in this case study, both in terms of reducing the production of fine sediments at source, and/or interrupting and managing the transport of such sediments before they reach the focus site.

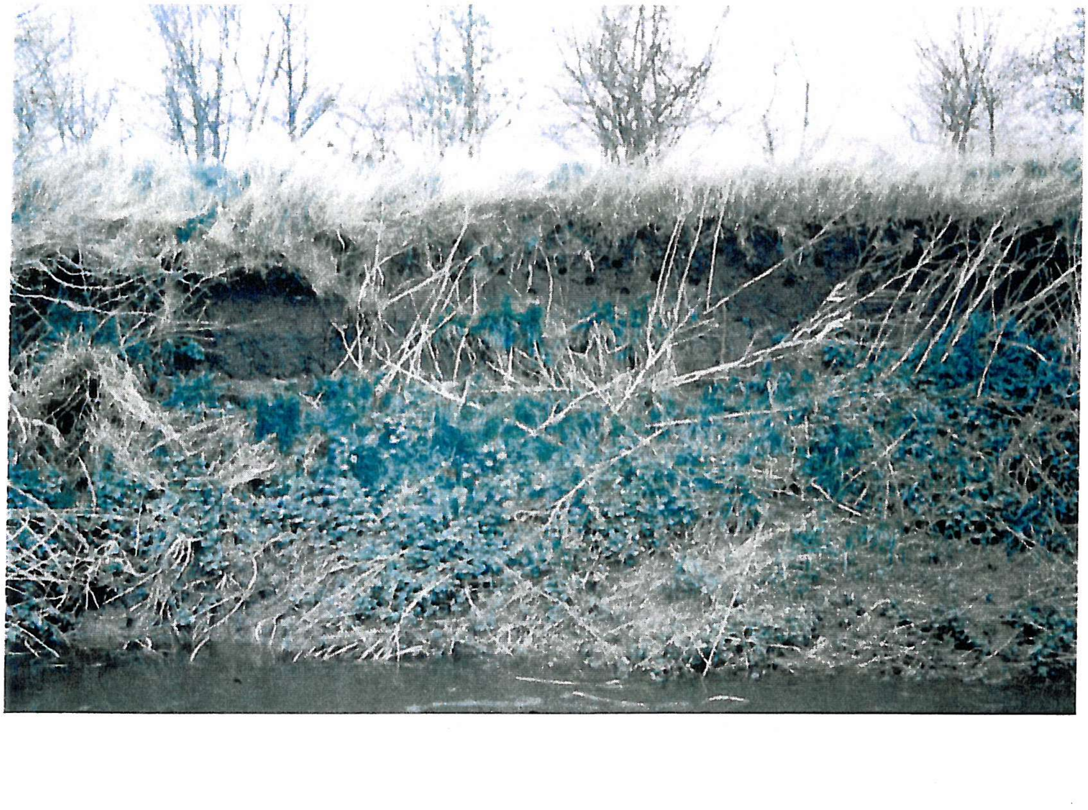
In terms of the additional objectives developed in the conclusions of the Shelf Brook case study, the need to audit the watercourses of a full catchment system, including tributaries, has been addressed by this study, and the wide distribution of the areas of active erosion across the catchment has shown the necessity of including as many minor watercourse as possible. This case study has also shown that the audit can be applied successfully to a catchment that contains a lot of structures and lengths of engineered channel. The significance of such engineering modification was shown in the distribution of certain types of deposition, in particular berms. Conclusions have also successfully been produced on the most efficient frequency and intensity of observation sampling strategies. This could be of great use in the future for reducing costs of subsequent catchment audits. The robustness of the audit method in terms of replicability and inter-observer variation has also been examined and found to be acceptable.

The successful developments above have served to forward the applicability and robustness of the geomorphological audit approach, and as such they have built greatly on the work of the first case study, however this case study has delivered more than this. It has succeeded in formalising the sediment issues that it identifies into the wider management objectives of the catchment. In other words it has taken its findings beyond the original Flood Defence audience and into the mainstay of environmental planning and management, i.e. inclusion of sediment issues in the catchment LEAP document. This is a positive step for the long-term sustainable management of the upper Mersey catchment.

4.9 Case Appendix 1: Photos Showing Examples of Different Erosion Types

Eroding Cliff

Stable Cliff

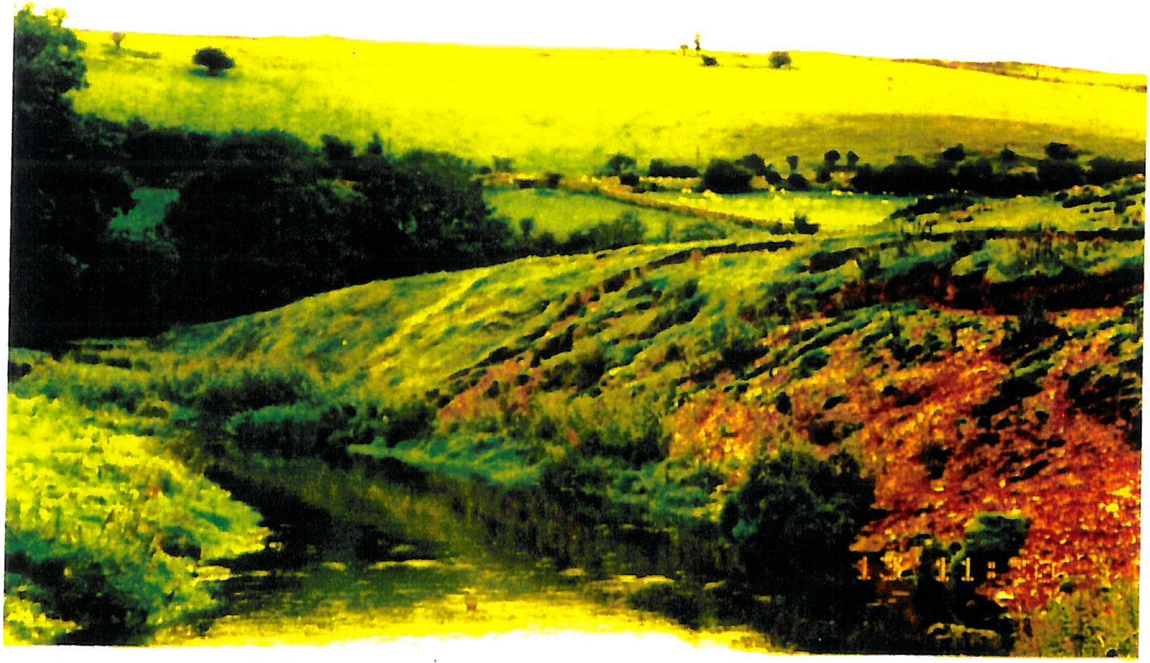


Slump

Toe Scour (foreground bank)

Mass Wasting (Creep)

Mass Wasting (Slide)

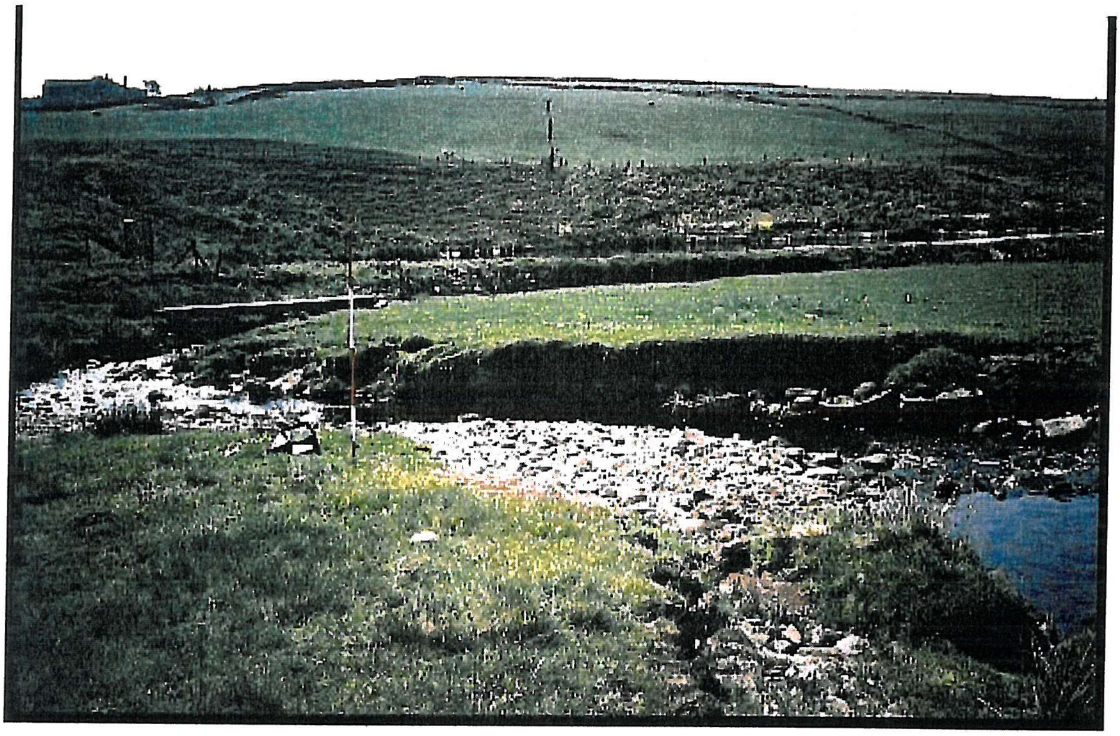


Mass Wasting (Wash) (from ploughed field at left bank)

Bed Scour

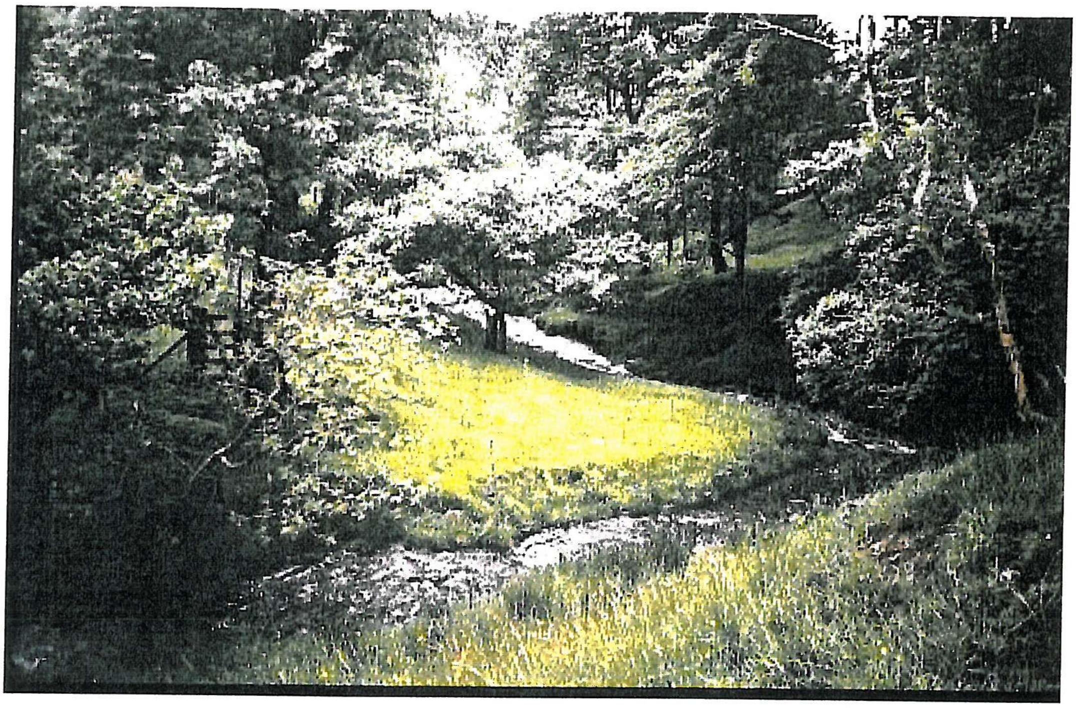
Case Appendix 2: Photos Showing Typical Examples of Sites in the Active Macro-Reaches of the Upper Mersey Area

Upper River Tame



Shelf Brook

River Sett



Lower River Goyt

Micker Brook

Lower River Tame

The River Mersey (focus area)

4.10 Case Appendix 3: Raw Data for Chi-Squared Tests of Statistical Similarity of Upper Mersey Audit Data Sampled From Different Populations

In the test results below DF = degrees of freedom and P-Value = significance level at which the two datasets are found to be from the same population.

Chi-Square Test - Continuous data (100%) and 50% Interval Sample (1:50int)

```
Expected counts are printed below observed counts

          100%  1:50int    Total
    1       10       10       20
         10.29     9.71

    2        7        6       13
          6.69     6.31

    3        6        4       10
          5.15     4.85

    4       14       14       28
         14.41    13.59

    5        9        8       17
          8.75     8.25

    6        7        8       15
          7.72     7.28

Total       53       50      103

Chi-Sq =  0.008 +  0.009 +
          0.014 +  0.015 +
          0.142 +  0.150 +
          0.012 +  0.012 +
          0.007 +  0.008 +
          0.067 +  0.071 = 0.515
DF = 5, P-Value = 0.992
1 cells with expected counts less than 5.0
```

Chi-Square Test - Continuous data (100%) and 50% Random Sample (1:50rand)

```
Expected counts are printed below observed counts

          100% 1:50rand    Total
    1       10       12       22
         11.32    10.68

    2        7        6       13
          6.69     6.31

    3        6        8       14
```

```
           7.20      6.80

     4       14        10        24
          12.35     11.65

     5        9         6        15
           7.72      7.28

     6        7         8        15
           7.72      7.28

 Total       53        50       103

 Chi-Sq =  0.154 +  0.163 +
           0.014 +  0.015 +
           0.201 +  0.213 +
           0.221 +  0.234 +
           0.213 +  0.226 +
           0.067 +  0.071 = 1.792
DF = 5, P-Value = 0.877
```

Chi-Square Test - Continuous data (100%) and 25% Interval Sample (1:25int)

```
Expected counts are printed below observed counts

          100%  1:25int    Total
     1      10        4       14
          6.81     7.19

     2       7        8       15
          7.29     7.71

     3       6        8       14
          6.81     7.19

     4      14       16       30
         14.59    15.41

     5       9        8       17
          8.27     8.73

     6       7       12       19
          9.24     9.76

Total       53       56      109

Chi-Sq =  1.497 +  1.417 +
          0.012 +  0.011 +
          0.096 +  0.091 +
          0.024 +  0.022 +
          0.065 +  0.062 +
          0.542 +  0.513 = 4.352
DF = 5, P-Value = 0.500
```

Chi-Square Test - Continuous data (100%) and 50% Random Sample (1:25int)

```
Expected counts are printed below observed counts
```

```
         100% 1:25rand    Total
    1      10        8       18
         8.75     9.25

    2       7        8       15
         7.29     7.71

    3       6        4       10
         4.86     5.14

    4      14       12       26
        12.64    13.36

    5       9       16       25
        12.16    12.84

    6       7        8       15
         7.29     7.71

Total      53       56      109

Chi-Sq =  0.178 +  0.168 +
          0.012 +  0.011 +
          0.266 +  0.252 +
          0.146 +  0.138 +
          0.819 +  0.775 +
          0.012 +  0.011 = 2.789
DF = 5, P-Value = 0.732
1 cells with expected counts less than 5.0
```

Chi-Square Test - Continuous data (100%) and 25% RHS Sample (RHS1:25)

```
Expected counts are printed below observed counts

         100% RHS(1:25)    Total
    1      10        4       14
         7.65     6.35

    2       7        4       11
         6.01     4.99

    3       6        8       14
         7.65     6.35

    4      14       12       26
        14.21    11.79

    5       9       12       21
        11.47     9.53

    6       7        4       11
         6.01     4.99

Total      53       44       97

Chi-Sq =  0.722 +  0.870 +
          0.163 +  0.196 +
          0.356 +  0.428 +
```

```
          0.003 +  0.004 +
          0.534 +  0.643 +
          0.163 +  0.196 = 4.278
DF = 5, P-Value = 0.510
2 cells with expected counts less than 5.0
```

Chi-Square Test - Continuous data (100%) and Expert Sample (Expert)

```
Expected counts are printed below observed counts

         100%   Expert    Total
    1      10        8       18
        10.26     7.74

    2       7        7       14
         7.98     6.02

    3       6        3        9
         5.13     3.87

    4      14       15       29
        16.53    12.47

    5       9        0        9
         5.13     3.87

    6       7        7       14
         7.98     6.02

Total      53       40       93

Chi-Sq =  0.006 +  0.009 +
          0.120 +  0.159 +
          0.148 +  0.196 +
          0.386 +  0.512 +
          2.921 +  3.871 +
          0.120 +  0.159 = 8.608
DF = 5, P-Value = 0.126
2 cells with expected counts less than 5.0
```

Chaper 5: Conclusions on the Overall Development and Application of the Geomorphological Audit Method

5.1 Development of the Methodology: A Review

A series of global objectives were initially developed, which would define and inform the development of the geomorphological audit methods of this project, and against which the success of the developing audit would be judged. These objectives reflected the need to develop a method that was both versatile and utilitarian. They were, in terms of *versatility*, the need to develop a method that was applicable to different physical habitats, catchment sizes, flood defence management objectives and flood defence 'life-stages'. In terms of *utility,* the following were identified; the need to demonstrate advantages over existing methods of geomorphological practice, and the need to identify any additional data needs, and demonstrate the tangible benefits of the audit.

Ideas of a simple audit classification system were initially developed in the first case study at the scale of a small catchment, but rejected as unsuited to producing useful flood defence management information. It was then demonstrated that an expanded rapid appraisal geomorphological audit could produce a classification system that was both statistically significant and geomorphologically logical. However, it was necessary to redefine the audit methods again, reinterpreting the information collected to produce a classification that concentrated on key environmental diagnostics pertaining to sediment sinks and sources, in doing so a finalised audit was produced. The results of this audit were successfully applied to local flood defence objectives at the 'life stage' of post-project appraisal by using readily available hydrological and geomorphological methods from the wider literature, leading to the development of an estimate of sediment-yield from the audit data. This estimate was then verified by comparison to monitoring data, collected in the field using traditional methods of 'geomorphological science'.

In the analysis of this first case study a number of interim weaknesses / areas for expansion were identified;

1. The need to apply the audit methods to a full catchment system of watercourses, and not just a single 'main-stem'.
2. The need to include areas of modified channel within the audit, to make it more widely applicable, as the majority of U.K. rivers systems contain some form of modification, (Raven et al, 1998).
3. The importance of looking at inter-observer variability, given that in the case of application to a larger catchment it would almost certainly require more than one geomorphologist to complete an audit within a reasonable working timescale.
4. The question as to whether or not it was possible to reduce the coverage of an audit from 100% of catchment reaches to only a sample of the total 'population' of watercourse reaches.
5. The need to collect more data on the types of erosion and deposition occurring, and the causes of that erosion and deposition, to inform management decisions.

The second case study saw the development of the audit methods to further explore the global objectives, and to address the areas of weakness / expansion that were identified above. The proforma was redesigned and a database was developed for the management and storage of audit data. Consultants were then retained to collect the audit data, due to the scale of the catchment area and the application of the audit to a large flood defence scheme at feasibility 'life-stage'. The audit data were then analysed, demonstrating the clear identification of areas of sediment sources, and the significant potential tangible benefits of applying the audit methods were demonstrated in this way.

5.2 The Application of the Audit re the Project Objectives: A Review

Objective	Application to different physical habitats	Objective 'Type'	Versatility

The audit methods have been successfully applied to a small upland catchment and a large catchment containing watercourses from upland headwaters to large lowland rivers. Collectively the two exhibit a range of landuses from rural agriculture to urban domestic and industrial development. However both catchments are in the same region, (Northwest England), both have similar soil types, underlying geologies and generic geomorphological long-term histories (i.e. their river valleys / floodplains both incorporate quantities of glacial drift and alluvial deposits). So while an initial positive affirmation could be made regarding the applicability of the audit methods to different environments, there is still perhaps a need to test the methods over a fully diverse range of locations, including catchments of characteristics such as fully lowland systems (with low altitude headwaters), baseflow / groundwater dominated systems or catchments on porous geologies. The methods perhaps also need to be applied to catchment systems that are very dynamic, for instance situations in which rivers are adjusting to destabilising changes. Subsequent to the research undertaken in this project a number of further applications have been undertaken nationally, using the geomorphological audit methods developed in the case studies documented above. These further studies do increase the diversity of the application of the audit methods, and more will be said about them in Section 5.4 below. There continues to be a need for more such studies to be undertaken before it is possible to proclaim that the geomorphological audit method is truly applicable to all U.K. physical habitats.

Objective	Application to different catchment sizes	Objective 'Type'	Versatility

This aspect has been touched upon in the paragraph above, and the work presented in the two case studies of this project has set a sound basis for the application of the audit methods at different scales. However, it might also be said that in addition to 'the large' and 'the small' in a U.K. catchment context, which are represented in this project, there may also be a need to examine in detail the application of the final audit methods to 'medium-sized' catchments. It is perhaps also worth noting that the use of a finite reach length, (i.e. 500 metres in the final version of the geomorphological audit), does place a finite minimum catchment size for which the audit methods may be used to identify spatially-diverse factors such as the environmental diagnostics amounting to sediment sources and sinks. It for instance possible that the 500-metre resolution would be too coarse accurately to pinpoint key areas of erosion and deposition in a catchment of (say) half the size of the Shelf Brook. Although, this does of course not necessarily mean that the audit methods could not be used for other purposes at the smallest of scales, (examples of such applications are given below in Section 5.4).

Objective	Application to different flood defence management objectives	Objective 'Type'	Versatility

The two case studies of this project have shown that the audit methods can be applied successfully to different aspects of flood defence maintenance application, i.e. the aspects of sediment-yield prediction and sediment source identification. The geomorphological audit as a tool is most naturally applicable to this type of sediment-based flood defence maintenance application. However, it may also be possible to apply the audit methods direct to other forms of flood defence application (design appraisal for instance, where audit methods might be used to inform design to minimise problems of sediment-transfer), or even to other areas of riverine management. Again further comments will be made on these aspects of wider applicability in Section 5.4 below.

Objective	Application to different flood defence life stages	Objective 'Type'	Versatility

This project has demonstrated that the audit methods may be applied to flood defence issues at feasibility and at post-project appraisal 'life-stages'. As indicated in the paragraph above, it might also be applied in the future to projects at design 'life-stage', or even to projects at construction, where audit methods could for instance help to locate temporary sediment trapping devices to optimise the retention of the unusually-high fine sediment loads that are an inevitable consequence of riverine construction works.

Objective	Demonstrate the advantages over existing methods	Objective 'Type'	Utility

The Shelf Brook case study initially demonstrated the advantages of the audit methods over firstly methods of engineering science, in that more accurate measures of sediment-yield, (the desired flood defence objective), were derived using the audit method than using any formulae based approach. This was primarily thought to be based such generic methods do not by design incorporate specific catchment sediment data, therefore they tend to assume an unlimited sediment supply, which is not the case in the majority of U.K. catchments, (Newson and Sear, 1997), therefore their yield estimates are not particularly accurate, particularly over the sort of extended periods of time which are applicable to gravel trap management.

The Shelf Brook case study also illustrated the basic advantages of the audit method over methods of geomorphological science, i.e. the ability to produce an estimate of sediment-yield that was close to the actual measurements derived from the field, without the time and cost implications of having to set up and maintain a monitoring programme over a period of years.

The advantages of the audit method over existing methods of engineering practice has been largely addressed in the consideration of tangible benefits particularly in the case of the Mersey study, (summarised below), where the existing methods used are those of engineering practice, and the major benefits that the audit can 'bring to the table' are in terms of a reduction in the need for such practices and therefore the delivery of cost savings.

The examination of the advantages of the audit over methods of geomorphological practice has been more complicated. The Shelf Brook case study described the advantages of a quantified classification system such as the geomorphological audit over simple or qualitative classification systems, such as those of Schumm (1977) or Rosgen (1996), as the ability to objectives estimates of the scale of geomorphological activity on a reach by reach basis, and thus to differentiate objectively between areas of, for instance, high or low sediment input. However, apart from the ability to speculate about the possible significance of large historical spate events, the benefits of the audit methods over other geomorphological data collection methods such as catchment baseline audit or fluvial audit, (Universities of Southampton, Newcastle and Nottingham, 1997), was not demonstrated. Although the applicability at the catchment scale, in terms of time savings, of the audit methods over detailed specialist methods, such as Bank Assessment Record Sheet, (the Universities of Southampton, Newcastle and Nottingham 1997), or a Stream Reconnaissance Sheet (Thorne 1998), was evident. The inclusion of data on the types and causes of erosion and deposition in the final audit method in the 2nd case study does however give the method certain advantages over existing methods such as catchment baseline audit or fluvial audit, as such data can be used to produce detailed management advice on a reach by reach basis, (in areas identified as geomorphological 'hot-spots'), targeting erosion for instance that is artificially enhanced, by suggesting measures appropriate to the type of erosion that is occurring.

Objective	Assess the need for additional data	Objective 'Type'	Utility

There has been shown to be a need for additional data in the case of the application of the audit methods to the derivation of sediment-yield, (Shelf Brook case study), as the data collected in the audit takes an 'instantaneous' measurement of geomorphological processes such as erosion and deposition, and therefore other techniques are required to extrapolate these measurements into rates over time. However, in terms of the identification of sediment sources, an instantaneous overview of geomorphological processes is adequate, and thus no additional data are required. The audit does not however, in its final form, account for potential changes in sources under, or subsequent to, the advent of major spate conditions. It also does not allow for the potential of geomorphological features to change inherently, (such as the ability of erosion scars to 'heal themselves'): these factors are discussed further in Section 5.3 below.

Objective	Show the tangible benefits of the audit approach	Objective 'Type'	Utility

The Shelf Brook case study illustrated that the estimated costs of undertaking the audit, (£1500-£2500) are an acceptable fraction of the total construction cost of the gravel trap (£20,000), such that they might feasibly be incorporated in a similar project in the future, either at design phase to size the trap, or at post project appraisal, (as in this case), to check that the capacity of an existing trap is adequate. The Mersey case study however, went on to demonstrate that major potential cost savings could be achieved by using the audit to identify fine sediment inputs at source and also to inform appropriate management actions to reduce inputs at those sources. Sample costs of £2000 per 500-metre reach were worked up (including an extrapolation to £50,000 to treat the worst 25 sites of active erosion in the catchment, representing half the hot-spots identified). Compared to the average annual maintenance costs of £70,000 such methods would clearly make sound financial sense if they could be seen to reduce sediment inputs by as little as 10% in the long term.

Objective	Apply the audit to a full catchment system	Objective 'Type'	Additional [13]

The Mersey case study clearly demonstrated the necessity of the inclusion of a wider field of watercourse reaches in the catchment analysis of sediment sources, as the distribution of such sources covered all the river systems of the catchment. The extent to which smaller watercourses should be included is a difficult question, as discussed in the case study, however limiting the audit to 'main river' reaches is a logical selection criteria, as the Environment Agency only has direct powers over such watercourses.

Objective	Apply the audit to modified watercourses	Objective 'Type'	Additional

This was an important development in the Mersey case study, as the majority of watercourses in the U.K. are modified, (Raven et al. 1998), and therefore the ability to apply the audit to such channels was a paramount element in meeting the objective of versatile applicability to different physical habitats detailed above. In the analysis of the audit results modification was found to be significant in determining the spatial distribution of certain types of deposits, in particular berms, (common features in widened channels).

Objective	Examine inter-observer variability	Objective 'Type'	Additional

The Mersey case study also successfully showed that the levels of inter-observer variability were acceptable, (+/- 30% or less for virtually all components of the audit). While less variability would obviously be desirable, and ways of achieving improvements will be discussed below 5.4, in the context of this form of rapid appraisal assessment such figures are not unreasonable.

13 Additional Objectives identified after the appraisal of the audit performance in Case Study 1.

Objective	Consider the potential to reduce the proportional coverage of the audit	Objective 'Type'	Additional

This aspect of the application of the audit methods to the latter case study is interesting in that the results produce a sound footing for the suggestion that it might be possible to reduce the sampling interval on large catchment audits to 50% coverage using an interval sampling method. This is important as it might, in future applications to similar large catchments, allow a decrease in the time / cost of an audit, and thus an increase in tangible benefits.

Objective	Collect more detailed data on types and causes of erosion / deposition to better inform management suggestions	Objective 'Type'	Additional

As indicated above, the inclusion of a greater range of information on types and causes of erosion and deposition in final audit form used in the Mersey case study was significant in that it meant that not only could key sediment sources be identified across the catchment, but that detailed management information could be given as to not only where to address erosion problems, but also how to address such problems. Also, the causal information could be used to separate 'natural' erosion from 'accelerated' erosion, and while it might not always be desirable to simply treat accelerated sites and leave natural ones untreated, the availability of this information for flood defence staff and environmental managers in general is important. This is because the continuation of natural erosion is often important from an ecological viewpoint, and from a geomorphological viewpoint it is necessary in any case as a natural part of the sediment-transfer system.

5.3 Remaining Limitations of the Geomorphological Audit Methods

Many strengths have been apparent in the application of the audit to the project objectives detailed above, not least are the ability to obtain accurate results quickly, and to inform flood defence management intelligently, as well as the encouraging cost-benefit indications. However, there are still a small number of issues that are yet to be resolved concerning the contents and application of the audit, that at present stand as limitations.

Such limitations include the fact that the audit, as an 'instantaneous' assessment of geomorphological catchment condition, does not address the potential for relative geomorphological change over time within an individual reach without intervention. In other words factors such as the ability of banks to 'heal themselves' of erosion problems, when for example live turf collapses onto an undercut profiles and establishes itself, are over-looked. Although some such features might at present be recorded as 'stable cliffs', they are not separated out in the analysis.

A related weakness of the audit methods, and perhaps a more serious one, is that in an effort to organise the data collected on erosion and deposition into types and causes for reasons stated above, the link to the separation of 'historical' and 'in-channel' sinks and sources that was achieved in the Shelf Brook case study has been lost. In doing this, the final version of the audit is now missing the capacity to extrapolate the observed geomorphological performance of the catchment to a past, or potential future, performance under the advent of major spate flows. This does perhaps present the greatest flaw in the development of the audit methods to date, and it is one that needs to be addressed if such the application of such methods is to be further expanded in the future.

Finally, an existing constraint on the audit is the inter-observer variability experienced, for while this is not excessive, as indicated above, any variability limits the absolute utility of a method. Therefore, there is perhaps need for the development of the audit keynotes into a more comprehensive user manual, of training for geomorphological observers to further standardise definitions, and of a accreditation scheme to ensure the quality of observers is high. The benefits of such actions have been demonstrated in the application and development of the River Habitat Survey, (Environment Agency, 1997).

5.4 The Further Application of Audit Methods, Subsequent to the Completion of the Mersey Case Study

Since the completion of the Mersey case study there have been a number of further applications of the geomorphological audit methods, using the final version of the proforma developed in the last case study, that are outside the scope of this research project. It is however perhaps worth detailing such applications briefly.

Table 5-1: Summary of Applications of Geomorphological Audit Techniques Since Completion of Mersey Case Study

Catchment	**Environment Agency Region**	Approximate number of sites included in audit	**Nature of Application**
River Eden	North West	500	Natural assets register
River Ribble	North West	400	Natural assets register
River Weaver	North West	300	'Sustainable rivers project'
Glaze Brook	North West	180	Natural assets register
River Camel	South West	150	Natural assets register
Sankey Brook	North West	150	'Integrated river basin management project'
River Tywi	Welsh	150	Flood defence maintenance
River Mimram	Thames	48	Water Resources low flow monitoring
River Bollin	North West	4	Monitoring river rehabilitation
Sugar Brook	North West	2	Monitoring river rehabilitation
Byne Brook	Midlands	2	Monitoring river rehabilitation
Padgate Brook	North West	1	Post-project appraisal of river rehabilitation

Table 5.1 above illustrates that the applications for which the geomorphological audit methods are now being use have now gone far beyond the realms of flood defence maintenance. The 'natural asset registers' of the Ribble, Camel Glaze and Eden are prepared by the Ecology sections of the relevant Environment Agency regions. The audit methods form one of a suit of riverine assessment tools that form such registers, and the results identifying, for example accelerated areas of erosion, are used to identify opportunities for environmental enhancements such as river rehabilitation schemes, in addition to identifying areas of environmental degradation. The Ribble audit was undertaken for the Environment Agency under contract by the Institute of Freshwater Ecology (with advice and input from the author co-ordinated through the River Habitat Survey (RHS), Lead Region Headquarters in Warrington), and has been considered a success. The Camel was undertaken by independent consultants in SW England, (with little interaction with the RHS Lead Region or the author), and has been less successful. This experience has increased the impetus for the development of a user manual / training and accreditation facilities for the geomorphological audit. The Eden project is currently ongoing, (scheduled finish December 2000). It is targeted towards the development of detailed natural asset registers for the subcatchments of the Lowther, Bela, Hilton Beck and Scandal Beck. It represents the largest single application of the geomorphological audit methods to date.

The 'Integrated River Basin Management Project', based on the Sankey catchment, was an Environment Agency pilot project designed to show how a Geographical Information System could be used to manage environmental catchment information, including geomorphological data. The audit data in this case were collected by Penny Anderson Associates, and the project was successful, gaining a lot of publicity, including a presentation to the current Chairman of the Environment Agency.

The Tywi project was also a success. In this case data were again collected by Penny Anderson Assocs., but the application was the same as the flood defence objectives of the Mersey case study of this project in that the audit formed a catchment wide assessment of sediment sinks and sources. The Tywi was however found to be extremely active and a new recording category (beyond >100 sq. / cubic metres) had to be defined as 'super macro' (observations in excess of 500 sq. / cu.m).

The Weaver audit was undertaken as a part of the Sustainable River Management project. This project seeks to quantify the impacts of unfenced livestock access to watercourses on sediment inputs. The audit was used to set the short lengths of highly monitored focus sites in a catchment wide context. The audit was undertaken by WS Atkins, (with advice and input from the author co-ordinated through the River Habitat Survey (RHS) Lead Region), with some success.

The data collection for the Mimram audit was undertaken in September 2000 by ENTEC Consultants, and the analysis of this data are currently ongoing (with advice and input from the author). This audit forms part of a suite of data that is being collected for baseline monitoring purposes in order to assess the impacts of proposed water resources abstractions of river water for industrial usage.

Finally the use of the audit to assess the river rehabilitation schemes of the River Bollin and the Sugar Brook at Manchester Airport's 2nd runway, has been as part of a suit of environmental monitoring tools designed to establish a baseline audit, of geomorphological activity amongst other things, against which to compare future developments. Similarly the Byne Brook application also forms part of an effort to collect baseline data to monitor the success of rehabilitation works. While the use of the audit at the Padgate Brook was in an effort to appraise the geomorphological development of a site, which despite extensive geomorphological input at design phase had sadly received no baseline geomorphological review post construction and no post project appraisal in its first five years. The Bollin, Sugar Brook and Padgate Brook projects were undertaken by the author, and the Byne Brook application was undertaken by ENTEC. Collectively the four projects illustrate one form of potential application for the audit at the very small scale, (as small an individual site in the case of the Padgate Brook). To date the application of the geomorphological audit methods, while concentrated in the North West, has in total been undertaken across five of the eight Environment Agency Regions.

In total audits at almost 2200 sites have been completed to date, (including the Mersey sites included in this work), using the geomorphological audit methods, this equates to 1100 kilometers of watercourses.

5.5 The Future

It is hoped that the future will see the continued application of the audit methods to further flood defence projects, but it is also hoped that the range of other applications will continue to expand across the sphere of Environment Agency activity. It however important to address the limitations outlined above and to action the development of the user manual, training and accreditation needs in order to facilitate this development.

Chaper 6: References

Ackers, P. and White, W.R., (1973) Sediment transport a new approach and analysis. *J.Hydraul. Div, ASCE*, 99 (HY11), 2041-2060.

Adenlof, K.A. and Wohl, E.E., (1994) Controls on bedload movement in a subalpine stream of the Colarado Rocky Mountains U.S.A. *Arctic and Alpine Research*, 26, 77-85.

Agostini, R., Coute, A., Malaguti, G. and Papetti, A. (1985) *Flexible linings in reno matresses and gabions for canals and canalised watercourses,* Officine Maccaferri S.p.A., Bologna, Italy.

Apmann, R.P. (1972) Flow processes in open channel bends, *Am. Soc. Civ. Eng. J. Hydr. Div.*, 98, Hy5, 795-799.

Asheson, A.R. (1968) *River control and drainage in New Zealand*, Ministry of Works, Wellington, N.Z.

Ashworth, P.J. (1987) *Bedload transport and channel changes in gravel bed rivers,* PhD. Thesis, University of Stirling.

Bagnold, R.A. (1966) An approach to the sediment transport problem from general physics. *U.S. Geol. Surv. Prof. Pap.*, 422-I.

Barsch, D., Happoldt, H., Mausbacher, R., Schrott, L. and Schukraft, G. (1994) Discharge and fluvial sediment transport in a semi-arid high mountain catchment, Agua Negra, San Juan, Argentina. In *Dynamics and geomorphology of mountain rivers*, eds. Ergenzinger, P. and Schmidt, K., Springer-Verlag, Berlin.

Bathurst, J.C., Graf, W.H. and Cao, H.H. (1987) *Bedload discharge equations for steep mountain rivers.* In *Sediment transport in gravel bed rivers*, eds. Thorne, C.R., Bathurst, J.C. and Hey, R.D., Wiley, N.Y.

Beaver, C. and Walker, J. (1998) 'Integrated interests: Earth heritage protection', *Earth Heritage*, 9, 14-15.

Becht, M. (1994) Investigations of slope erosion in the northern limestone Alps. In *Dynamics and geomorphology of mountain rivers*, eds. Ergenzinger P. and Schmidt K., Springer-Verlag, Berlin.

Bezinge, A., Clark, M.J., Gurnell, A.M. and Warburton, J. (1989) The management of sediment transported by glacial melt-water streams and its significance for the estimation of sediment-yield. *Ann. Glaciology*, 13, 1-5.

Billi, P. (1993) Steep mountain streams: processes and sediment. *Z. Geomorph. N.F.*, Bd88, 1-16, Berlin.

Birch, S. (1999). *Assessing bedload movement on the upper Irwell river*, unpubl. undergraduate dissertation, University of Lancaster.

Bosman, J.J., Van de Velden, E.T.J.M. and Hulsbergen, C.H., (1987) Sediment concentration measurements by transverse suction. *Coastal Engineering*, 11, 353.

Bray, D. I. (1972) *Generalised regime type analysis of Alberta rivers*, Ph.D. thesis, University of Alberta.

Brice, J.C. (1984) Planform properties of meandering rivers. In *River meandering, Proceedings of confererence rivers 1983*, ed. Elliot C.M., ASCE, 1-15.

Bridge, J.S., (1981) Hydraulic interpretation of grain-size distributions using a physical model for bedload transport. *J. of Sedimentary Petrology*, 51(4), 1109-1124.

Briggs A.R., Walker, J.G. and Sear, D.A. (1996) *Catchment audit of the Rivers Brent and Crane*, Unpubl. report to NRA (Thames Region).

British Standards Institution, (1980) *Methods of measurement liquid flow in open channels: Velocity-area methods*. BS3680, 3A, British Standards Institution, London.

Brookes, A. (1985) Downstream morphological consequences of river channelisation in England and Wales, *Geographical Journal*, 151, 57-62.

Brookes, A. (1994) *Fluvial Geomorphology: Presentation to the environmental managers group meeting*, Publ. In house, Environment Agency, London.

Brookes, A. (1996) *A "new" approach to river management: The use of geomorphology*. Proc. R & D National Workshop, Birmingham.

Brookes, A. and Sear D.A. (1996) Geomorphological principles for restoring channels. In *River Channel Restoration: Guiding principles for sustainable projects,* eds. Brookes A. and Shields F.D., Wiley, London.

Brown, C.B. (1950) Sediment transportation, Chap.XII. In *Engineering hydraulics*, ed. H. Rouse, Wiley, N.Y.

Bullen and Partners Ltd. (1992) *Glossop Flood Alleviation Scheme Modelling Report*. Report to the National Rivers Authority, Warrington.

Bunte, K. (1992) Particle number grain-size composition of bedload in a mountain stream. In *Dynamics of gravel bed rivers*, eds. Billi, P., Hey, R.D., Thorne, C.R. and Tacconi, P., Wiley, N.Y.

Busskamp, R., (1994) The influence of channel steps on bed load transport in mountain torrents: case study using the radio tracer technique 'petsy'. In *Dynamics and geomorphology of mountain rivers*, eds. Ergenzinger P. and Schmidt K., Springer-Verlag, Berlin.

Butcher D.P., Labadz J.C., Potter A.W.R. and White P. (1992) Assessment of catchment erosion in the southern Pennines, United Kingdom, using reservoir sedimentation monitoring. *Erosion and sediment transport monitoring programmes in river basins, (Proc. Of the Oslo Symp. Aug 1992).* IAHS Publ., 210, 443-454.

Butler, P.R. (1977) Movement of cobbles in a gravel-bed stream during a flood season. *Geol. Soc. Am. Bull.*, 38, 1072-1074.

Campbell, A.J. and Sidle, R.C. (1985) Bedload transport in a pool riffle sequence of a coastal Alaska stream. *Water Resources Bulletin*, 21, 579-580.

Carey, W.C. (1966) Comprehensive river stabilisation. *ASCE J. Waterways and Harbours Division,* 92, 59-86.

Carle, F.L. and Strub, M.R. (1978) *A new method for estimating population size from removal data,* Longman, London.

Carling, P.A. (1983) Particulate dynamics, dissolved and total load, in two small basins, Northern Pennines, UK, *Hydrol. Sci. J.,* 28, 355-375.

Carling, P.A. and Reader, N.A. (1989) Structure, composition and bulk properties of stream gravels. *Earth Surface Process and Landforms,* 7, 349-365.

Chow, V.T. (1959) *Open-Channel Hydraulics*, McGraw-Hill Book Co, New York.

Church, M., McLean, D. and Wolcott, J.F. (1987) River bed gravels sampling and analysis. In *Sediment transport in gravel bed rivers*, eds. Thorne C.R., Bathurst J.C. and Hey R.W. Wiley, Chichester, 43-79.

Clowes, A. and Comfort, P. (1982) *Process and Landform*, Oliver and Boyd, Edinburgh.

Colby, B.R. and Hembree, C.H. (1955) Computations of total sediment discharge Niobrara, near Cody, Nebraska. *U.S.Geol. Surv. Water Supply Pap.,* 1357.

Colby, B.R. (1964) Practical computation of bed-material discharge. *J. Hydraul. Div., ASCE*, 90 (HY2), 3483, 217-246

Cooper, N. and Hooke J. (1999) *Geomorphological Impact of Croys*, Environment Agency, Exeter.

Crickmore, M.J. and Aked, R.F. (1975) Pumped samplers from measuring sand transport in tidal waters. *Proc. IERE conf. On instrumentation in oceanography*, Bangor, Wales, 311-326.

Curd, W.C. (1921) Bank protection and restoration, a problem in sedimentation. *ASCE Trans.*, 84:146, 303-330.

D'Agostino, V. (1994) Indagine sullo scavo a valle di opere tasversali mediante modello fisico a fondo mobile. *L'Energia Elettrica,* 71(2), 37-51.

Danish Hydraulic Institute (1999) Website information on MIKE SHE and MIKE BASIN from *www.dhi.dk.*

Darby S.E. and Thorne C.R. (1990) *Fluvial Maintenance: A literature review and extended bibliography for the construction industry research and information assoc.*, University of Nottingham.

Davis, W.M. (1899) The geographical cycle. *Geographical Journal,* 14, 481-504.

Downs, P.W., Gregory K.J. and Brookes A. (1991) How integrated is river basin management. *Environmental Management*, 15 (3), 299-309.

Downs, P.W. and Gregory K.J. (1993) The sensitivity of river channels in the landscape system, In *Landscape sensitivity*, eds. Thomas, D.S.G. and Allison, R.J., Wiley, N.Y.

Downs, P.W. (1994) *'River Bollin Geomorphological Evaluation in the Region of the Proposed Manchester Second Runway'*, Unpubl. report, NRA.

Downs, P.W., Wood A.L. and Thorne C.R. (1997) *Fluvial Audit of the Upper River Severn.* Unpubl. report, Nottingham University Consultants Ltd.

Downward, S.R. (1995) Information from topographic survey. In *Changing river channels*, eds. Gurnell, A. and Petts, G., Wiley and sons, 303-323.

Drisko, J.B. (1933) 'Improving the Oder river'. *Civil Engineering*, 3, 314-318.

DuBoys, P. (1879) Le Rohne et les rivieries a lit affoulillable. *Annales des ponts et chaussees,* 5 (18), 141-195.

Duck, R.W. and McManus, J. (1994) A long-term estimate of bedload and suspended sediment-yield derived from reservoir deposits. *J. Hydrol.*, 159, 365-373.

Dunne, T. and Leopold, L.B. (1978) *Water in Environmental Planning*, Freeman, San Francisco.

Einstein, H.A. (1950) The bedload function for sediment transportation in open channel flow. *U.S.Dept. of Ag., Soil Cons. Service Tech. Bull.,* 1026.

Engelund, F. and Hanson, E. (1967) *A monograph on sediment transport in alluvial streams,* Teknisk Forlag, Copenhagen.

Environment Agency (1995) *The quality of rivers and canals in England and Wales*, Environment Agency, Bristol.

Environment Agency (1996) National sampling procedures manual, (Vol. 25), Quality management system for environmental sampling, Environment Agency, Bristol.

Environment Agency (1997) *River Habitat Survey: Field survey guidance manual*, Publ. in house, Warrington.

Environment Agency (1998) *Soil erosion run-off rates and sheep-overgrazing*, R&D Project P2C(96)6, Environment Agency Stationary Office, Norwich.

Environment Agency (1999a). *Flood Defence in the North West*, publ. in house, Warrington.

Environment Agency (1999b). *Waterway bank protection: a guide to erosion assessment and management*, R&D Technical summary 11, Stationary Office, London.

Environment Agency (2000a). *Farming: sustainable rivers in the Northwest,* publ. in house, Warrington.

Environment Agency (2000b). *National Framework Agreement for Engineering and Environmental Services: Specification for Tenders*, unpubl. report, London.

Ergenzinger, P.J. and Custer, S.G. (1983) Determination of bedload transport using naturally magnetic tracers: first experiences at Squaw creek, Gallatin county, Montana. *Water Resources Research*, 19, 187-193.

Fiddes, D. and Clifforde, T. (1990) River Basin Management: Developing the Tools. *J. Institute of Water and Environmental Management,* 4 (1), 92-97.

Fish, I.L. (1983) Partech turbidity monitors: Calibration with silt and the effects of sand. *Technical note OD/TN1*, Hydraulics Research, Wallingford.

Fisk, H.N. (1952) Mississippi river valley geology relation to river regime. *ASCE Transactions*, 117, 667-689.

Furse, M.T., Moss, D., Wright, J.F. and Armitage, P.D. (1984) The influence of seasonal and taxonomic factors on the ordination and classification of running water sites in Great Britain and on the prediction for their macro-invertebrate communities. *Freshwater Biology,* 14, 257-280.

Gardiner, J.L. (1990) River catchment planning for land drainage, flood defence and the environment. *J. Institute of Water and Environmental Management,* 4 (5), 442-450.

Gaudet, J.M., Roy, A.G. and Best, J.L. (1994) Effect of orientation and size of Helley-Smith Sampler on its efficiency. *J. Hydraul. Eng.*, 120:6.

Gee, D.M. (1984) Predictions of the effects of a flood control project on a meandering stream. Hydrologic Engineering Centre, *U.S. Army Corps. Eng., Tech. pap.,97,* Davies, CA.

Gilbert, G.K. (1914) Transportation of debris by running water. *U.S. Geol. Surv. Prof. Pap.*, 86.

Gintz, D., Hassan, M.A. and Schmidt, K. (1996) Frequency and magnitude of bedload transport in a mountain river. *Earth Surface Processes and Landforms*, 21, 433-445.

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

Gomez, B. and Church, M. (1989) An assessment of bedload transport formulae for gravel bed rivers. *Water Resources Research,* 25(6), 1161-1186.

Halcrow (Sir William Halcrow and Co.) and H.R. Wallingford (1999) *ISIS Sediment: User Manual*, publ. In house H.R. Wallingford, Oxon.

Hall, B.R., Thomas, W.A. and Pearson, M.L. (1992) Computing bedload discharge and channel adjustment in a cobble-bed river for flood control and channel design. In *Dynamics of gravel bed rivers*, eds. Billi, P., Hey, R.D., Thorne, C.R. and Tacconi, P., Wiley, N.Y.

Hankundy, R.W. (1971) System and method for preventing erosion. *Official Gazette*, 893:1, 53.

Hassan, M.A., and Church, M. (1992) The movement of individual grains on the streambed. In *Dynamics of gravel bed rivers*, eds. Billi, P., Hey, R.D., Thorne, C.R. and Tacconi, P., Wiley, N.Y.

Hassan, M.A., Church, M. and Ashworth, P.A. (1993) Virtual rate and mean distance of travel of individual clasts in gravelbed rivers. *Earth Surface Process and Landforms*, 17, 617-627.

Havis, R.N., Carlos, V.A. and King, J.G. (1996) Modelling sediment in gravel bedded streams using HEC-6. *J. Hydraul Eng.*, 122, 559-564.

Hemphill, R.W. and Bramley, M.E. (1989) *Protection of river and canal banks*, Butterworths, London.

Hey, R.D. and Thorne, C.R. (1983) Accuracy of surface samples from gravel bed material, *J. Hydraulic Eng.*, 109, 849-851.

Hey, R.D., Heritage, G.L., Tovey, N.K., Boar, R.R., Grant, N. and Turner, R.K. (1991) *Streambank protection in England and Wales*, R & D Note 22, NRA.

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

Hjulstrom, F. (1935) Studies of the morphological activities of rivers as illustrated by the River Fyris, *Bulletin of the Geographical Institute*, University of Uppsala, 25, 221-227.

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

Hurley, M.A. (1992) Modelling bedload transport events using an inhomogeneous gamma process. *J. Hydrolgy,* 138, 529-541.

Hydrologic Engineering Centre (HEC) (1977) *HEC-6 Scour and deposition in rivers and reservoirs User's manual,* U.S. Army Corps. Eng., Davies, CA.

Jaeggi, M.N.R. (1992) Effect of engineering solutions on sediment transport. In *Dynamics of gravel bed rivers*, eds. Billi, P., Hey, R.D., Thorne, C.R. and Tacconi, P., Wiley, N.Y.

Johnson, C.O. (1950) Similarity in scour below a spillway. *MSc Thesis, University of Minnesota,* Minneapolis.

Keller, E.A. and Brookes, A. (1984) 'Consideration of meandering in channelization projects: selected observations and judgements. In *River Meandering. Proc. Conf. Rivers,* ed. Elliot, C., ASCE, Vicksburg, 384-397.

Keown, M.P., Oswalt N.R., Perry, E.B. and Dardeau, E.A. (1977) *Literature Survey and Preliminary Evaluation of Streambank Protection Methods*, U.S. Army Engineer Waterways Experiment Station, Mississippi.

Knighton, A.D. (1973) Riverbank erosion in relation to streamflow conditions, River Bollin-Dean, Cheshire. *East Midlands Geographer,* 5, 416-426.

Komar, P.D. and Carling, P.A. (1991) Grain sorting in gravel-bed streams and the choice of particle sizes for flow-competence evaluations. *Sedimentology*, 38, 489-502.

Kondolf, G.M. and Matthews, W.V.G. (1986) Transport of tracer gravels on a coastal California river. *J. Hydrol.*, 85, 265-280.

Laronne, J.B. and Reid, I. (1993) Very high rates of bedload sediment transport by ephemeral desert rivers. *Nature*, 366, 148-150.

Laronne, J.B., Reid, I., Meerovich, L. and Powell (1995) Selection of gravel transport formulae for stream modelling. *J. Hyd. Eng.,* 121(7), 567-569.

Laursen, E.M. (1952) Observations on the nature of scour. *Proceedings of Fifth Hydraulic Conference,* Bulletin 34, University of Iowa, Iowa, 179-197.

Laursen, E.M. (1958) The total sediment load of streams. *J.Hydraul. Div, ASCE,* 84 (HY1).

Lawler, D.M. (1987) Bank erosion and frost action: an example from South Wales. In *International Geomorphology, Part 1,* ed. Gardiner, V., Wiley, 575-590.

Lawler, D.M. (1993) The measurement of river bank erosion and lateral channel change: a review. *Earth Surface Processes and Landforms,* 18, 777-821.

Lawler, D.M., Harris, N. and Leeks, G.J.L. (1997) Automated monitoring of bank erosion dynamics: applications of the novel photo-electric erosion pin (PEEP) system in upland and lowland river basins. In *Management of landscapes disturbed by channel incision,* eds. Wang, S.Y. et al, Oxford press, Mississippi, 249-255.

Lawrence, P. (1996) *Guidelines on field measurement procedures for quantifying catchment sediment-yields*. Rep. OD/TN77, H.R. Wallingford, Oxon.

Leopold, L.B., and Wolman, M.G. (1957) River channel patterns: braided, meandering and straight. *U.S. Geol. Surv. Prof. Pap.,* 282-B.

Lewin, J. (1972) Late stage meander growth. *Nature*, 240, 116.

Lopes, V.L. and Meyer, J. (1993) Watershed management programme on Santiago Island, Cape Verde. *Environmental Management,* 17(1), 51-57.

Malloch, A.J.C. (1988) *'Vespan II – User Manual'*, University of Lancaster.

Martin, Y., and Church, M. (1995) Bed material transport estimated from channel surveys: Vedder river, British Columbia. *Earth Surface Processes and Landforms*, 20, 347-361.

Meyer-Peter, E., Favre, H. and Einstein, H.A. (1934) Neuere versuchsresultate uber den geschiebetrieb. *Schweiz, Bauzig,* 103, 147-150.

Meyer-Peter, E. and Muller, R. (1948) Formulas for bedload transport. *Report of the second meeting of international hydraulics research*, Stockholm, Sweden, 39-64.

Milne, J.A. and Sear, D.A. (1997) Modelling river channel topography using GIS. Int J. Geographical Information Science, 11(5), 499-519.

Mohanty, R.B., (1988) An overview of suspended sediment samplers with particular reference to IS:3913 bottle sampler. *Proc. Indo-British workshop on sediment measurement and control,* Chandigarh, India, 22-24.

Moore, R.J. and Newson, M.D. (1986) Production storage and output of coarse sediments: natural and artificial influences as revealed by research catchments. *J. of the Geol. Soc.*, 143, 921-926.

Mosley, M.P. (1975) Meander cutoffs on the River Bollin, Cheshire 1872-1973. *Revue de Geomorphologie Dynamique,* 24, 21-31.

Mosely, M.P. (1978) Bed material transport in the Tamaki river near Dannevirke, North Island, New Zealand. *New Zealand J. Sci.*, 21, 619-626.

Mosely, M.P. (1987) The classification and characterisation of rivers. In *River channels: adjustments and processes*, ed. Richards K.S., Blackwells.

Nanson, G.C. and Beach, H.F. (1977) Forest succession and sedimentation on a meandering-river floodplain, northeast British Columbia, Canada. *Journal of Biogeography*, 4, 229-251.

National Parks Service (1983) Automatic water samplers for field use. *Rep.83-1*, Water resources field support laboratory, Colorado State University, U.S.

National Rivers Authority (1994) *River Irwell Catchment Management Plan*, Publ. in house, Warrington.

National Rivers Authority (1995) *River ROCH Comprehensive Flood Alleviation Scheme: River Modelling Report,* Unpubl. report, Warrington.

National Rivers Authority (1995) *River Habitat Survey: Field survey guidance manual*, Publ. in house, Warrington.

Newson, M.D. (1986) River basin engineering – Fluvial geomorphology. *J. Inst. Water Engineers and Scientists,* 40(4), 307-324.

Newson, M.D. (1992) *Land, Water and Development*, Routledge, London.

Newson, M.D. and Sear, D.A. (1992) *Environmental change and the management of fisheries, river Ehen, Cumbria*. Unpubl. report to Egremont Angling club.

Newson, M.D. and Sear, D.A. (1997) The role of geomorphology in monitoring and managing river sediment systems. *J. CIWEM*, 11, 264-270.

Nevins, T.H.F. (1965) River classification with particular interest to New Zealand. *Proceedings, 4th N.Z. Geography Conference,* Dunedin, 83-90.

Nixon, M. (1966) Flood regulation and river training. In *River Engineering and Water Conservation Works,* ed. Thorn, R.B., Butterworths, London, 239-271.

Nolan, P. and Gutherie, N. (1996) River rehabilitation in an urban environment: examples from the Mersey basin, N.W. England. *Proc. Conf. European Centre for River Restoration*, Denmark, 1-12.

Noorbergen, H.H.S. (1993) Multitemporal analysis of a braiding river. In *Proceedings International Symposium, Operationalisation of Remote Sensing*, 3, 161-168.

North West Water (1976) *River Mersey Flood Control and Improvement Scheme*, NWW Engineering Group, Unpubl. report, (RP-35H-06).

Orr, H. and Quinn, A. (1998) *River Leith fluvial audit*, Report to the Environment Agency, Publ. in house, University of Lancaster.

Padmore, C.L., Newson, M.D. and Charlton, E. (1997) Instream habitat in gravel bed rivers, identification and characterisation of biotopes. In *Gravel bed rivers in the environment, Proc. of the 4th international gravel bed rivers conference*, Oregan State University.

Parker, G. and Andres, D. (1976) Detrimental effects of river channelization. *Proc. Conference of Rivers*, ASCE, 1248-1266.

Parker, G. (1990) Surface based bedload transport relation for gravel rivers. *J. Hydraul. Res.*, 28, 417-436.

Popov, I.V. (1964) Hydromorphological principles of the theory of channel processes and their use in hydrotechnical planning. *Soviet Hydrology*, 2, 188-195.

Powell, J.W. (1875) *Explanation of the Colorado River and its tributaries*, Smithsonian Institute, Washington D.C.

Raven, P.J., Holmes, N.T., Dawson, F.H., Fox, P.J.A., Everard, M., Fozzard, I.R. and Rouen, K.J. (1998) *River habitat quality the physical character of rivers and streams in the UK and Isle of Man*, Report 2, Environment Agency, Bristol.

Reading, H.G. (1986) *Sedimentary environments and facies*, Blackwell, London.

Reed, S. (1995 *Irishmans bridge River Liza, Cumbria: Fluvial audit,* Unpubl. National Rivers Authority report, Reading.

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

Reid, I., Laronne, J.B. and Powell, D.M. (1995) The Nahal Yatir bedload database: sediment dynamics in a gravel bed ephemeral stream. *Earth Surface Process and Landform*, 20, 845-857.

Rickenmann, D. (1994) Bedload transport and discharge in the Erlenbach stream In *Dynamics and geomorphology of mountain rivers*, eds. Ergenzinger P. and Schmidt K., Springer-Verlag, Berlin.

Ritter, D.F. (1979) The effects of channelisation on a high-energy river. *Environmental Geology*, 3, 29-38.

River Restoration Centre. (1999) *River restoration manual of techniques.* River Restoration Centre, Silsoe.

Rosgen, D. (1994) A classification of natural rivers. *Catena,* 22, 169-199.

Rosgen, D. (1996) *Applied River Morphology*, Wildland Hydrology, Colorado.

Schmidt, K. and Ergenzinger, P. (1992) Bedload entrainment, travel lengths, rest periods - studied with passive (iron, magnetic) and active (radio) tracer techniques, *Earth Surface Processes and Landforms,* 17, 147-165.

Schmidt, K. (1994) River channel adjustment and sediment budget in response to a catastrophic flood event (Lainbach catcment, southern Bavaria). In *Dynamics and geomorphology of mountain rivers*, eds. Ergenzinger P. and Schmidt K., Springer-Verlag, Berlin.

Schoklitsch, A. (1934) Der geschiebetrieb und die geschiebefracht. *Wasserkraft Wasserwirtschaft,* 4, 1-7.

Schumm, S.A. (1963) A tentative classification of alluvial river channels. *U.S. Geological Survey Circular,* 477, Washington, D.C.

Schumm, S.A. and Lichty, R.W. (1963) Channel widening and floodplain construction along Cimarron River, in south-western Kansas. *U.S. Geological Survey Professional Paper*, 352D.

Schumm, S.A. (1977) *The fluvial system*, Wiley and sons, N.Y.

Schumm, S.A., Harvey, M.D. and Watson, C.C. (1984) *Incised Channels: Morphology, Dynamics and Control*, Water Resources Publications, Littleton, Colorado.

Schumm, S.A. (1991) *Scientific approaches to earth science: 10 ways to be wrong,* Cambridge University Press, Cambridge.

Scott Wilson Kirkpatrick & Co. (1996) *Whittle Brook rehabilitation scheme: Post project appraisal*, Report to the Environment Agency, Warrington.

Scott Wilson Kirkpatrick & Co. (1999a) *River Mersey Flood Alleviation Scheme, Draft Hydrological Report,* Environment Agency, Warrington.

Scott Wilson Kirkpatrick & Co. (1999b) *River Mersey Flood Alleviation Scheme, Project Initiation Document*, Environment Agency, Warrington.

Sear, D.A. (1994) River restoration and geomorphology, *Aquatic Conservation: Marine and Freshwater Ecosystems,* 4, 169-177.

Sear, D.A., Darby, S.E., Thorne R. and Brookes, A. (1994) Geomorphological approach to stream stabilization and restoration: case study of the Mimmshall Brook, Herts., U.K., *Regulated Rivers: Research and Management,* 9, 205-223.

Sear, D.A. and Newson, M.D. (1994) *Sediment and gravel transportation in rivers including the use of gravel traps*, R & D Project Record 384/3/T, NRA.

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

Sear, D.A. (1996) Sediment transport processes in pool-riffle sequences, *Earth Surface Processes and Landforms*, 21, 241-262.

Sear, D.A. (1998) A preliminary analysis of the morphological adjustment within and downstream of a lowland river subject to a river restoration. *Aquatic Conservation: Marine and Freshwater Ecosystems,* 8, 167-183.

Sear, D.A, Lee, M.W.E.L., Oakey, R.J., Carling. P.A. & Collins, M.B. (2000) Coarse sediment tracing technology: a review, in *Tracers in Geomorphology*, ed. Foster, I.D.L., J.Wiley & Sons, Chichester, UK.

Selby, M.J. (1985) *Earth's changing surface an introduction to geomorphology.* Oxford University Press, Oxford.

Sharpe, N.T. (1994) *"The worst in living memory",* N.T. Sharpe, Glossop.

Shaw, E.M. (1988) *Hydrology in practice*, Chapman and Hall, London.

Shields, A. (1936) Anwendung der aenlichkeitsmechanik und der turbulenzforchung auf die geschiebebewegung. *Mitteilungen der preussischen versuchsanstalt fur wasserbau und schiffbau,* Berlin, Germany, Translated to English by W.P.Ott and J.C. van Uchelen, C.I.T., Pasadena, Calif.

Sikka, D.R. (1973) Highlights of flood protection works done on River Narmoda at Hoshongabad in Madhya Pradesh State, India. *Proc. Int. Assoc. Hydr. Res., Symposium on River Mechanics,* Asian Institute of Technology, Bangkok, Thailand, 329-339.

Slaymaker, H.O. (1972) Patterns of present sub-aerial erosion and landforms in mid-Wales. *Inst. Br. Geogrs. Trans.*, 55, 47-68.

Sneed, E.D. and Folk, R.L. (1958) Pebbles in the lower Colarado River, Texas, a study in particle morphogenesis, *Journal of Geology*, 66, 114-150.

Stelczer, K. (1981) *Bedload transport: theory and practice.* Water resources publ., Littleton, Colarado.

Thornbury, W.D. (1969) *Principles of geomorphology*, Wiley and Sons, New York.

Thorne, C.R., Reed, S. and Doornkamp, J. (1994) *A procedure for assessing river bank erosion problems and solutions*, R & D Report, NRA.

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

Thorne, C.R. (1998) *Stream Reconnaissance Handbook,* Wiley, Chichester.

Tingsanchali, T. and Supharatid, S. (1996) Experimental investigation and analysis of HEC-6 river modelling group. *Hydrological Processes*, 10, 747-761.

Toffaleti, F.B. (1969) Definitive computations in sand discharge in rivers. *J.Hydraul. Div, ASCE,* 95 (HY1) 225-248.

University of Newcastle (1998) *Sediment and gravel transportation in rivers: a procedure for incorporating geomorphology in river maintenance*, Environment Agency, National Centre for Risk Analysis and Options Appraisal, Guidance note 23, London.

Universities of Nottingham, Newcastle and Southampton (1997) *Geomorphological approaches to river management*, Environment Agency R&D Project 661, National Centre for Risk Analysis and Options Appraisal, London.

Universities of Nottingham, Newcastle and Southampton (1998) *River geomorphology: A practical guide*, Environment Agency R&D Project 661, Centre for Risk Analysis and Options Appraisal, London.

Universities of Southampton and Newcastle (1995) *River channel typology for catchment and river management,* National Rivers Authority R & D project 539/NDB/T, Bristol.

Universities of Southampton and Newcastle (1999) *River channel typology: feasibility for use in river management,* Environment Agency R&D Technical report W87, Bristol.

U.S. Agricultural Research Service (1961) *A universal equation for predicting rainfall-erosion losses,* Report 22-26.

Vanoni, V.A. (1975) Sedimentation engineering, *ASCE Task Committee*, N.Y.

Walker, J. (1995) *A study of sediment processes in the Yermasoyia reservoir and catchment, Cyprus*, M.Sc. Thesis, Unv. of Wales, Bangor.

Walker, J. and Briggs, A.R. (1996) *River Rother at Woodhouse Mill, a geomorphological site assessment.* Unpubl. report to the Geodata Institute, University of Southampton.

Walker, J. and Sear, D.A. (1996a) *Post project appraisal of the geomorphological affects of weir removal on the Chalvey Ditch, Bucks*, Unpubl. report to National Rivers Authority (Thames Region).

Walker, J. and Sear, D.A. (1996b) *River Crane flood alleviation scheme, Bath Rd. geomorphological post project appraisal*, Unpubl. report to National Rivers Authority (Thames Region).

Walker, J. (1997a) *River Roch flood alleviation scheme geomorphological report*, Unpubl. Environment Agency Report, Warrington.

Walker, J. (1997b) *River Keer geomorphological investigation*, Unpubl. Environment Agency Report, Warrington.

Walker, J. (1997c) *River Trannon geomorphological report*, Unpubl. Environment Agency Report (to Shrewbury office), Warrington.

Walker, J. (1998a) *Pendle Water flood alleviation scheme geomorphological investigation*, Unpubl. Environment Agency Report, Warrington.

Walker, J. (1998b) *Glossop flood alleviation scheme, Shelf Brook gravel trap post project appraisal*, Unpubl. Environment Agency Report, Warrington.

Walker, J. (1998c) *Upper Mersey Catchment Geomorphological Survey*, Unpubl. Environment Agency Report, Warrington.

Walker J., Naura M. and Diamond M., (1998) The Use of the River Habitat Survey to Identify Sites for River Rehabilitation, *Newsletter of the European Centre for River Restoration*, **2**(1), 6-7.

Walker, J. and Walker, P. (1998) River processes and recreation: A case study of the River Brock in the Forest of Bowland AONB, *Countryside Recreation*, 6(2), 7-9.

Walker, J. (1999) The Application of Geomorphology to the Management of River Bank Erosion. *Water and Environmental Management Journal*, 13(4), 297-300.

Walker, J. (2000) *River Eden at Gt. Musgrave: Sediment Transport Modelling Report*, Unpubl. Environment Agency Report, Warrington.

Walling, D.E. and Webb, B.W. (1982) Sediment availability and the prediction of storm-period sediment-yields. In *Recent developments in the explanation and prediction of erosion and sediment-yields*, ed. Walling, D.E., Intl. Ass. Hydrol. Sci. Publ. No. 137, 327-337.

Wang, M-H. and Han, Y. (1994) Riverbed Variations Modelling in Practice. In *Hydroinformatics*, ed. Verwey, V., Minns, K., Babovic, V. and Maksimovic, M., Balkema, Rotterdam, 723-730.

Warburton, J. and Davies, T. (1994) Variability of bedload transport and channel morphology in a braided river hydraulic model, *Earth Surface Process and Landform,* 19, 403-421.

Weiss, F.H. (1994) Luminor experiments in the Saalach and Salzach rivers. In *Dynamics and geomorphology of mountain rivers*, eds. Ergenzinger P. and Schmidt K., Springer-Verlag, Berlin.

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

White, I., Mottershed, D.N. and Harrison, S.J. (1984) *Environmental Systems*, Unwin-Hyman, London.

Whitehouse, R.J.S. and Hardisty, J. (1988) Experimental assessment of two theories for the effect of bedslope on the threshold of bedload transport. *Marine Geology,* 79, 135-139.

Williams, D.T. (1977) Effects of dam removal: an approach to sedimentation, Hydrologic Engineering Centre, *U.S. Army Corps. Eng Tech. pap.*,50, Davies, CA.

Wolman, M.G. (1954) Factors influencing erosion of a cohesive river bank. *American Journal of Science,* 257, 204-216.

Wood-Smith, R.D. and Buffington, J.M. (1996) Multivariate geomorphic analysis of forest stream: implications for assessment of land use impacts on channel condition. *Earth Surface Process and Landforms*, 21, 377-393.

Yalin, M.S. (1963) An expression for sediment transportation. *J.Hydraul.Div., ASCE,* 95 (HY3), 221-250.

Yang, C.T. (1972) Unit stream power and sediment transport. *J.Hydraul.Div., ASCE,* 98 (HY10).