QUANTIFYING CATCHMENT-SCALE COARSE SEDIMENT DYNAMICS IN BRITISH RIVERS

by

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It has become increasingly clear that river channel sediment dynamics must be taken into account within British flood risk management because changes in channel morphology resulting from sediment transfer can have an impact on channel flood capacity. It is also recognised that an understanding of catchment-scale sediment dynamics is desirable with respect to many other aspects of river management. However, despite this recognition, application of existing approaches that account for coarse sediment dynamics has been limited within British river management.

Based on these considerations, this study aims to develop and substantiate a new approach that quantitatively accounts for catchment-scale coarse sediment dynamics in British rivers. These research efforts contribute to the activity of the Flood Risk Management Research Consortium (http://www.floodrisk.org.uk/)

A review of the availability and accuracy of data sources useful to considerations of coarse sediment dynamics reveals that only discharge, channel slope, and channel width can be represented widely at the catchment-scale. As a result, none of the approaches currently available to account for coarse sediment dynamics were found to be both scientifically robust and practically applicable at the catchment-scale. This leads to the conclusion that the most suitable approach to account for coarse sediment dynamics at the catchment-scale in British rivers is a reach-based sediment balance model, using no more than slope, width and discharge data.

A new reach-based sediment balance model, ST:REAM (Sediment Transport: Reach Equilibrium Assessment Method), is developed. It has several unique features including: representation of the entire catchment network; automatic delineation of the catchment network into functional reaches using a zonation algorithm; application of a new general formula for the prediction of bed surface material transport rate; and adoption of an assumption that makes it unnecessary to collect bed material size data. The outputs from ST:REAM are in the form of predicted Capacity Supply Ratios which compare the annual mass of

sediment predicted to enter a reach with the annual mass of sediment predicted to leave it.

Initial assessment of ST:REAM using two test catchments shows that it can produce a reasonable representation of observed, broad-scale sediment dynamics. The accuracy of its predictions decreases when attempting to incorporate downstream variability in bed material size into the model, and scale issues are encountered when attempting to increase the resolution at which reaches are identified by the zonation algorithm.

ST:REAM has many potential applications within river management, but it is of most value when providing a broad-scale picture of predicted reach sediment balances throughout the drainage network. As well as the practical applications of ST:REAM, the research contained within this thesis has important theoretical implications, relating both to the insights it provides on catchment-scale sediment dynamics in particular and methodological and foundational developments in the field of sediment studies more generally.

This research forms part of a multi-disciplinary programme undertaken by the Flood Risk Management Research Consortium (http://www.floodrisk.org.uk). The Consortium is funded by the UK Engineering and Physical Sciences Research Council (EPSRC) under grant GR/S76304/01, jointly with the UK Natural Environment Research Council (NERC), the Joint UK Department for Environment, Food and Rural Affairs and Environment Agency Flood and Coastal Erosion Risk Management R&D programme, the Scottish Executive, the Rivers Agency (Northern Ireland) and UK Water Industry Research. Specifically, this PhD was supported by a three-year EPSRC studentship (EP/P502632) at the School of Geography, University of Nottingham.

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When you can measure what you are speaking about and express it in numbers, you know something about it; but when you cannot express it in numbers, your knowledge is of a meagre and unsatisfactory kind; it may be the beginning of knowledge, but you have scarcely in your thoughts advanced to the state of science, whatever the matter may be.

Attributed to Lord Kelvin; source unknown

Chapter One: Introduction

1.1 Accounting for sediment dynamics within the Flood Risk Management Research Consortium

This thesis forms a component of a major programme of studies into the prediction and management of flood risk by the Flood Risk Management Research Consortium (FRMRC - see http://www.floodrisk.org.uk/): an interdisciplinary partnership of academic and industrial researchers from across the British Isles. The consortium aims to develop tools and techniques to support more accurate flood forecasting and warning, improve flood management infrastructure, and reduce flood risk to people, property and the environment (Huntingdon *et al.*, 2004). The consortium approach favoured by the FRMRC offers not only the scientific advances that would be expected of separate research projects but also the extra benefit of a collegiate framework. This type of approach was adopted to enable multi-disciplinary research activity in complex multi-scale research areas (Cluckie, 2008). Addressing flood risk management in a holistic way was deemed as being essential to ensure a complete and seamless integration of management options (Huntingdon *et al.*, 2004). The first phase of the FRMRC was launched in 2004 and completed in 2007. Its second phase began in 2007 and is due to end in 2011.

It was recognised from its inception that the FRMRC cannot cover all the topics that are of importance to flood risk management (FRMRC, 2004). It therefore adopted an organisational structure that addresses the six research ‘Priority Areas’ identified as being of key importance at ‘Flooding Research Workshops’ organised by EPSRC during 2002. These key Priority Areas are supported by two cross-cutting areas: Priority Area 8: Morphology and Habitats; and Priority Area 9: Risk and Uncertainty (Figure 1.1).

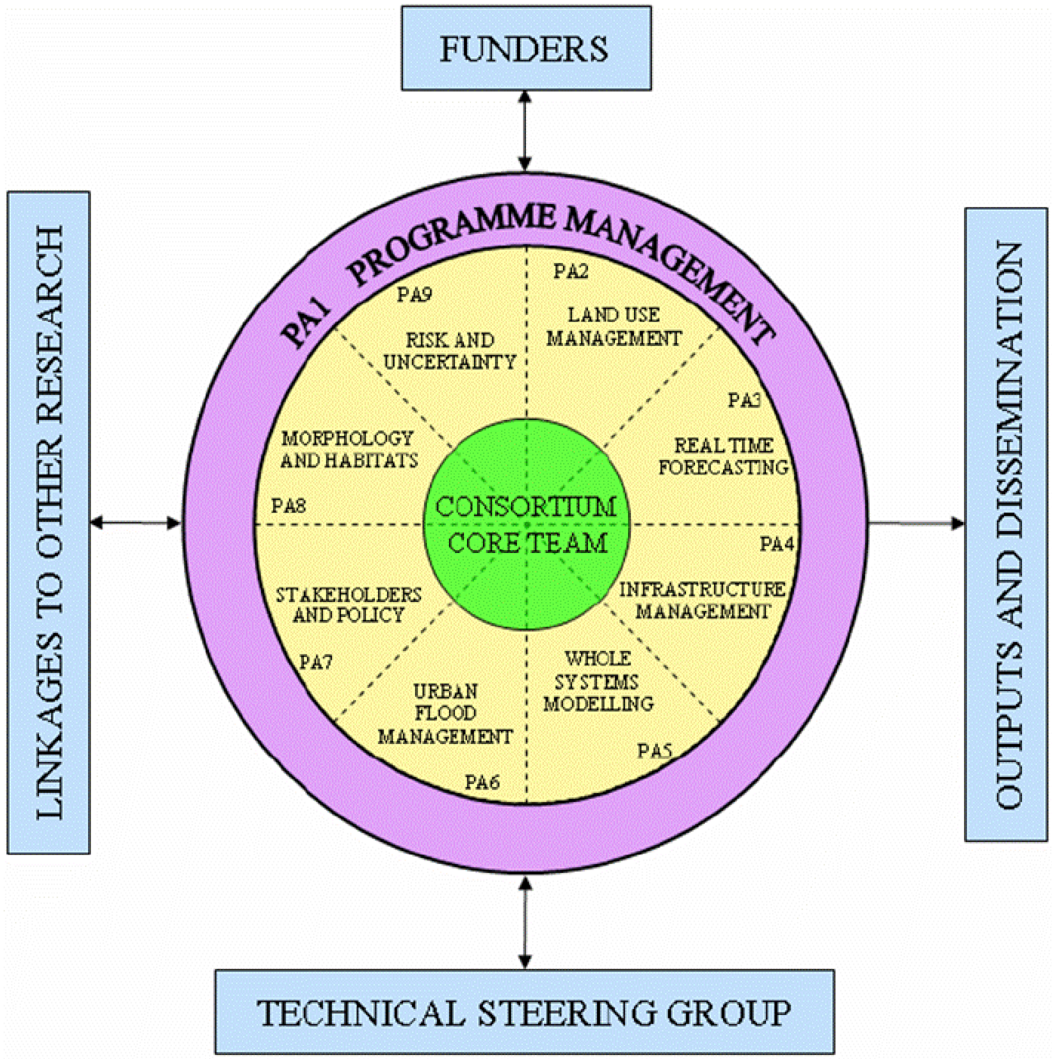

Figure 1.1 Schematic of FRMRC1 Priority Areas. Taken from Cluckie (2008).

Priority Area 8 (Morphology and Habitats) was created on the basis that extant flood management seldom accounts for sediment transfer in the fluvial system despite the fact that disruption of sediment dynamics is known to impact future flood risk and damage valuable habitats (FRMRC, 2004). A key research issue within this Priority Area was identified as being an inability to predict how a particular river will respond morphologically through the formation and modification of zones of erosion and sedimentation. This inability represents a major impediment to improved understanding of fluvial dynamics, sediment-related habitats and their links to flood risk management. The aim of Priority Area 8 was therefore to develop, prove and disseminate the analytical tools and insights needed to account for sediment dynamics, morphological responses and habitat impacts associated with flood management (FRMRC, 2004).

Table 1.1 provides the original research aims of each of the Work Packages contained within research Priority Area 8. Work Package 8.1 was originally concerned with the development of a quantitative alternative to the Environment Agency's Fluvial Audit. In the event, research efforts within FRMRC Work Package 8.1 resulted in the compilation of a versatile tool-box of sediment transport and transfer analysis methods and models to quantitatively support hydromorphologically-sustainable flood risk management (FRMRC, 2008). The tool-box incorporates a range of different approaches that span a range of requirements in terms of data input, technical knowledge and costs (time and money) and generate output resolutions which range from indicative to diagnostic and spatial scales from whole catchments to short river reaches (Thorne *et al.*, 2006). The six models currently included in the toolbox are: the Stream Power Screening Tool; the River Energy Audit Scheme (REAS); the sediment transport module of the Hydraulic Engineering Centre's River Analysis System (HEC-RAS 5.0); the Sediment Impact Assessment Model, embedded in HEC-RAS (HEC-RAS SIAM); ISIS Sediment; and the Cellular Automaton Evolutionary Slope and River model (CAESAR).

During compilation of the FRMRC 'Sediment Tool-box', it was recognised that there was an important gap between the data necessary to run existing quantitative models of the sediment transfer system, and the data that is widely available within British rivers at the catchment-scale. As a result, this Ph.D. study was initiated to contribute to the existing suite of tools by developing a new approach capable of accounting quantitatively for catchment-scale coarse sediment dynamics in British rivers. The research performed within this study is, therefore, strongly affiliated with, though not contained within, Work Package 8.1 of the first phase of the Flood Risk Management Research Consortium.

Table 1.1 Details of Work Packages within FRMRC1's Priority Area 8. Taken from FRMRC (2004).

WP	Description
8.1	*Quantitative Fluvial Audit Technique* - Will convert existing Environment Agency Fluvial Audit into a tool capable of identifying causal links between upstream erosion and downstream deposition, generating quantitative sediment flux data, and clarifying morphology-flood defence interactions. Deliverables will include enhanced software, guidance and training on Quantitative Fluvial Audits and uptake of an Enhanced River Habitat Survey method.
8.2	*Morphology, Habitat and Infrastructure Interactions* - Will investigate and characterise interactions between flood defence operations/infrastructure, morphology and habitats for different types of flood defence infrastructure and styles of channel change in the River Wharfe, by applying QFA method. *Deliverables*: Validated approach to accounting for and predicting interactions between morphology, habitats and infrastructure. Uptake of Enhanced River Habitat Survey and QFA methods, integration of morphological response and habitat models.
8.3	*Contaminated Sediments: Assessing Environmental and Public Health Risks* - Develops existing TRACER cellular model of sediment erosion, dispersal, storage and remobilisation into a numerical tool capable of identifying pathways between diffuse sources of contaminated sediment and downstream rural and urban flood sediment deposits. Deliverables will include a numerical model capable of identifying causal links between diffuse sources of contaminated sediments and flood deposits for analysis of environmental and public health risks associated with sediment-related pathogens, parasites and pollutants.
8.4	*Sustainable Development of Floodplains and Wetlands* - Involves a multi-disciplinary study of floodplain morphology and management that builds on the multi-scale field experiment on land-use management in *Land-use* Priority Area, together with studies of Stakeholder Behaviour, Policy and Decision Support Methods in the *Stakeholder and Policy* Area. Work based on one upland and one lowland case study. Deliverables will focus on the science base for new rural land management and planning guidance for sustainable flood management that is commensurate with increased biodiversity and habitat protection and a Case Study of integrated, context specific, multi-functional, flood risk management for the River Trent in concert with stakeholders.

As a result of its funding sources, one of the over-arching philosophies of the Flood Risk Management Research Consortium is the importance of linking fundamental research to the needs of end users (Figure 1.2). It was therefore considered imperative that the research performed within this Ph.D. study be mindful of the requirements of potential end-users. This led to early recognition that uptake by scientists and engineers involved in river management would depend crucially on any new, quantitative modelling approach being applicable based on data that is widely available at the catchment-scale.

However, not only should the final product of this work be genuinely useful in identifying and solving sediment related problems in British rivers, but also the process by which it is derived should provide a window on future research, and support improved understanding of catchment-scale sediment dynamics. It is envisaged that the findings reported in this thesis will inform development of the next generation of whole-system models by indicating how they might be made capable of including and accounting for sediment in the river system.

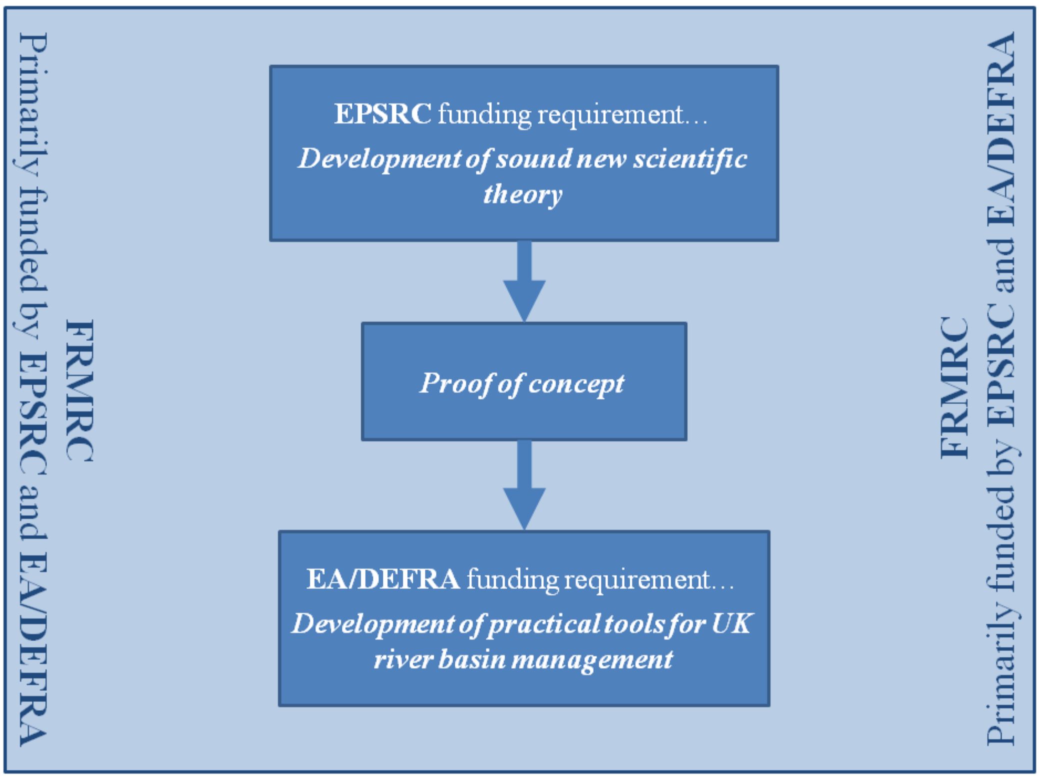

Figure 1.2 Over-arching research philosophy of the FRMRC. Modified from (Thorne et al., 2006).

1.2 Research rationale, aims and objectives

Due to a growing need for river managers to assess coarse sediment dynamics at the catchment-scale, and a shortage of methods for doing so that are both scientifically robust and practically utilizable, it is necessary:

…to develop and substantiate a new approach that quantitatively accounts for catchment-scale coarse sediment dynamics in British rivers.

An attempt to satisfy this need provides the rationale behind this thesis. As there is no simple hypothesis under investigation within this study, an applied strategic approach is adopted with the primary aim being the development of a 'best practice' procedure for quantitatively accounting for catchment-scale coarse sediment dynamics in British rivers. The thesis focuses on achieving this through successful fulfilment of the following research aims and objectives:

Aim 1 is to identify the need for river managers to account for catchment-scale coarse sediment dynamics and review the historical progress made in understanding these dynamics (Chapter Two). From this aim, the following objectives are derived:

- Identify the importance of coarse sediment dynamics within river catchment management;
- Describe how understanding coarse sediment dynamics has become more important following recent paradigm shifts within British river management;
- Describe how understanding coarse sediment dynamics has become more important in light of current and predicted future changes in catchment process drivers;
- Review the historical progress made by researchers attempting to explain how coarse sediment transport impacts on river channel morphology.

Aim 2 is to create a framework of requirements for an approach that quantitatively accounts for catchment-scale coarse sediment dynamics in British rivers (Chapter Three). From this aim, the following objectives are derived:

- Evaluate the data currently available and useful to the analysis of coarse sediment dynamics at the catchment-scale in British rivers;

- Critically appraise the scientific reliability and practical utility of currently available approaches to assessing coarse sediment dynamics.

Aim 3 is to develop a new approach that quantitatively accounts for catchment-scale coarse sediment dynamics in British rivers (Chapters Four, Five and Six). From this aim, the following objectives are derived:

- Identify the most appropriate framework for assessing coarse-scale sediment dynamics at the catchment-scale;
- Derive the individual components that comprise a new approach to quantitatively account for catchment-scale coarse sediment dynamics in British rivers;
- Assemble and describe the new approach for quantitatively accounting for catchment-scale coarse sediment dynamics in British rivers

Aim 4 is to substantiate the developed approach as a scientifically appropriate and practically useful means of accounting for coarse sediment dynamics in British rivers (Chapter Seven). From this aim, the following objectives are derived:

- Test the developed approach in trial applications to two test river catchments;
- Compare the outputs of the approach against observations of channel morphological status;
- Evaluate factors influencing the accuracy of the developed approach.

Aim 5 is to consider the implications of the developed approach for both the practical management of British river catchments and for academic treatment of coarse sediment dynamics (Chapter Eight). From this aim, the following objectives are derived:

- Discuss the potential value of the developed approach within British river management;

- Discuss the implications of the findings of the thesis for the way in which the academy views catchment-scale coarse sediment dynamics.

1.3 Thesis structure

The overall thesis structure is shown schematically in Figure 1.3.

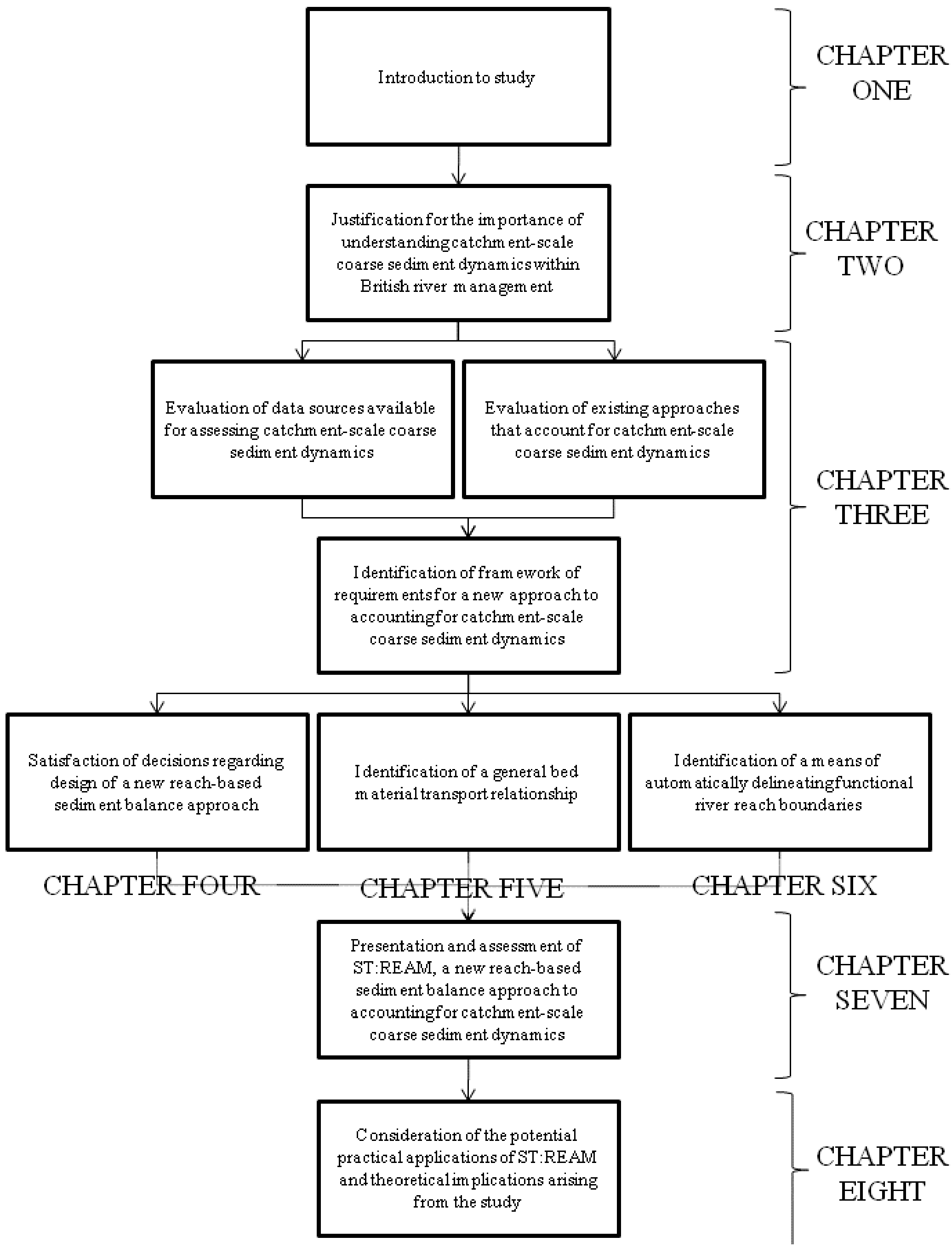

Figure 1.3 Thesis structure

Chapter One has introduced a brief background and justification for the thesis. Based on this justification, a research rationale has been identified and a series of research aims and objectives necessary to complete that mission statement have been set out.

Chapter Two aims to justify the importance of accounting for catchment-scale coarse sediment dynamics within British river management and explores the historical progress made in understanding these dynamics. After introducing why coarse sediment dynamics have always been important for river management, this chapter goes on to explain how this importance has been enhanced due to changes both in the way we manage rivers and in the drivers influencing how they operate. Once the need for understanding coarse sediment dynamics has been established, the remainder of this chapter explores the historical progress made by other researchers who have attempted to explain how coarse sediment transport impacts upon channel morphology.

Chapter Three aims to review existing data and techniques available for assessing catchment-scale coarse sediment dynamics in order to understand the setting within which any new approach must function. The data sources available to represent each of the relevant factors are considered both in terms of their accuracy, and their usefulness to an approach seeking to account for coarse sediment dynamics at the catchment-scale. Each of the existing approaches to accounting for coarse sediment dynamics are evaluated in terms of both their scientific robustness and their suitability for widespread application at the catchment-scale. Based on these reviews, decisions are made regarding the type of approach most suitable for accounting for catchment-scale coarse sediment dynamics.

Chapter Four describes the development of a new approach to accounting for coarse sediment dynamics at the catchment-scale. Building on the basic approach identified at the close of Chapter Three, Chapter Four identifies questions that must be answered in order to finalise the approach. The remainder of the chapter attempts to answer each of these questions within the constraints identified at the end of Chapter Three.

Chapter Five introduces a means of automatically discretising a drainage network based on functional reach boundaries for use within the new approach. Various definitions of the term ‘reach’ within river science are considered before a number of statistical methods for identifying functional reach boundaries are introduced and tested on a data sequence describing sediment transport capacity along the main stem of the River Taff in South Wales. A preferred zonation algorithm for identifying functional reach boundaries is selected and practical consideration is given to how it may be incorporated into the catchment-scale model. Finally, alternative applications for automatic functional reach zonation algorithms are discussed.

Chapter Six develops a generalised bed material transport relationship for use within the catchment-scale approach. Previous attempts to derive transport relationships are reviewed and arguments concerning why they may be considered to have failed are made. A large database of bed-load transport data is collated and presented, along with a number of potential explanatory flow parameters that are associated with sediment transport. Details regarding the methodology used to identify the most appropriate parameter and to derive a general relationship predicting bed material transport rate are provided before the results are presented and discussed. Finally, a methodology for applying the general transport relationship within the new approach is outlined.

Chapter Seven presents and assesses ST:REAM, the modelling approach to accounting for catchment-scale coarse sediment dynamics developed in this thesis. After the model has been presented, the advantages of model assessment over model validation and falsification are discussed. Two test catchments, the River Taff in South Wales and the Afon Einon in mid-Wales are introduced, and the observed sediment status for each is described. The outputs from ST:REAM for each catchment are compared to the observed sediment status, and the impacts of introducing bed material variability and different reach scales on ST:REAM's outputs are investigated.

Chapter Eight presents some conclusions drawn from the research performed in the preceding chapters. The potential applications of ST:REAM within British river management are considered before various theoretical implications resulting from the research are discussed. Finally, a reflection upon the findings of the thesis is used to inform a number of potential future research directions.

Chapter Two: Rationale and background - the importance of understanding catchment-scale coarse sediment dynamics in British rivers

2.1 The importance of coarse sediment dynamics

Rivers are agents of erosion and transportation, carrying the water and sediment supplied to them from the land surface to the oceans. Catchment weathering, surface and sub-surface processes produce sediment which rivers transport from land-based ‘sources’ to oceanic ‘sinks’. Estimates of the global sediment yield delivered to the oceans annually range from 8,300-51,000 million tonnes, with a most rigorous estimate of 20,000 million tonnes (Walling and Webb, 1996). The processes that deliver these sediment loads result in net denudation of the landscape and therefore play an important role in shaping the planet’s physical landscape. Understanding the dynamics of rivers as sediment transfer systems can improve our ability to effectively manage the way in which we interact with the physical environment.

The sediment load carried by rivers can be broken down on the basis of three different types of definition: source; transport mechanism; or measurement method (Table 2.1). When defining sediment load based on its source it can be separated into two components: the *wash load*, which comprises particles finer than those usually found in the bed and moves readily in suspension; and the *bed material load*, which includes all sizes of material found in appreciable quantities in the bed (Simons and Senturk, 1992). The bed material load may either be transported as *bed-load*, through rolling, sliding or saltation, when the weight of particles in transit is supported by the bed, or as *suspended load*, when particles are transported within the main body of the flow by turbulent mixing processes (Simons and Senturk, 1992). This thesis is concerned with the transfer of sediment responsible for geomorphological change and is therefore focussed on bed material load because of its influence on the adjustment of channel form. However, there is significant confusion in the distinction between wash load and bed material load as it depends upon an arbitrarily selected size division based on the material present on the bed, which itself is strongly dependent on antecedent flow conditions. No formal attempt to reconcile this semantic uncertainty is made within this thesis, and therefore instead reference is largely made to ‘coarse sediment’, which is loosely associated with bed material, but primarily identified as consisting of the sediment fractions that are important in influencing channel morphology.

Table 2.1 Classification of the sediment load carried by rivers (after Thorne et al., 1998)

Sediment Source	Transport Mechanism	Measurement Method
Bed material load	*Bed load*	*Unmeasured load*
	Suspended load	*Measured load*
Wash load		

The studies aiming to quantify global sediment yields introduced above tend to ignore the coarser products of catchment erosion within their estimates. Eroded coarse sediment is generally not transferred into the oceans, and is instead redistributed from areas of high relief to zones of lower relief, where it is retained in a form of temporary storage (Gomez, 1991). In fact, due to a combination of selective transport and particle attrition, coarse material transported as bed-load accounts for less than 10% of the sediment that is delivered to continental margins (Meade *et al.*, 1990). However, coarse sediment transport is of great importance in shaping terrestrial landscapes (Gomez, 1991), largely because of the fact that it is generally *not* conveyed through to the oceans. Evidence of its importance is apparent in geological records, as a significant proportion of the geological column consists of material containing particles coarser than those transported primarily by suspension (Meade *et al.*, 1990). It is because coarse sediment is transported less easily that it is more important in affecting the physical forms within river catchments: it is temporarily stored as the material comprising river channel boundaries, whilst finer sediment fractions are generally transferred into the oceans.

At the reach-scale, channel morphology is a reflection of the spatial pattern of coarse material movement (Dietrich and Smith, 1984; Meade, 1985; Ashworth and Ferguson, 1986; Lane and Richards, 1997). River channel morphology is controlled by the interplay between hydraulic conditions, the resistance of materials in the channel perimeter and the quantity and calibre of material delivered from upstream (Gomez, 1991). Since coarse material transport provides the major process linkage between these factors, prediction of likely contemporary and future river channel morphology requires an understanding of coarse sediment dynamics.

River practitioners have recognised, if not fully understood, the importance of coarse sediment dynamics since the turn of the 20th Century. In fact, practical imperatives were largely responsible for the establishment of fluvial geomorphology as a recognised science. Clifford (2008) describes how, on the 8th December 1904, the California Miners' Association petitioned the President to launch an investigation into erosion and sedimentation in the Sacramento and San Joaquin valleys. Following complaints from farmers concerning river instability and flooding, the local hydraulic mining industry had been laid to waste when restraints on the discharge of material into navigable waterways were imposed in 1884. An estimated $100,000,000 of property was left idle (Clifford, 2008). The miners were:

...firmly convinced that by a rational application of the laws governing the deposition of sediment from torrential streams, the industries of hydraulic mining and agriculture can both be carried on in this region, not only without prejudice to each other but to their mutual advantage;..Whereas this question is primarily a geological one and can be solved only be geologists who have devoted their lives to the study of erosion and sedimentation...

(Gilbert, 1917: 13)

The matter was subsequently investigated by Karl Grove Gilbert (1917) a geologist who pioneered the science of fluvial geomorphology by investigating how the delivery of sediment from hydraulic mining influenced river channel forms and processes. As a result of his studies, Gilbert (1917) argued in favour of the miners' case by showing that thirty years after the original problems, the rivers had readjusted to the enhanced sediment supply.

Similarly, the European exponents of fluvial geomorphology were both driven by, and informed a practical need to understand how coarse sediment dynamics were impacted on by channel flows, and subsequently impacted on channel geometry. Progress in European fluvial geomorphology was particularly impelled by colonial engineering efforts. In India and Pakistan, the combined experiences of several generations of canal engineers resulted in the formulation and successive refinement of 'regime theory' for alluvial channels (Clifford, 2008). Based on their practical experience, it became clear to canal engineers that both slope and channel shape impacted upon the transfer of channel boundary sediment, and were therefore of direct significance to canal stability.

In contemporary times, optimal utilisation of water resources involves balancing water, food and power supply with flood alleviation, navigation, recreation and conservation, which together necessitate planning considerations at the catchment-scale (Richards, 2004). The majority of catchment-scale management objectives are both strongly influenced by, and impact on the movement of coarse sediment. For example, attempts to control river flow using physical structures for power generation or water supply directly impede coarse sediment transfer so that the dams act as hinge points in a disrupted erosion/deposition system (Newson, 1992). Manipulation of the characteristics of catchment surface area for agriculture, urban development or forestry alters not only sediment yield directly, but also hydrological response which consequently affects the transport capacity of the river channel system (Henshaw, 2009). In turn, discontinuities in the natural transfer of coarse sediment through the fluvial system can increase flood risk (Lane *et al.*, 2007), and nick-point progression as a result of natural base-level level change can cause serious damage to land responsible for crop production (Simon, 1989).

Along with catchment-scale management, significant interaction with individual river channels means that an understanding of how fluvial morphological dynamics operate at the reach-scale is vital. Both the channelisation of natural streams to improve navigability or accelerate the passage of flood peaks, and the construction of artificial channels for both irrigation and navigation require appropriate channel designs. Channel widths, depths and gradients must pass discharges at a velocity sufficient to maintain transport of sediment without silting, but not so excessive that bed and banks are eroded (Blench, 1957). More than 8,500km of channelisation works were undertaken in England and Wales between 1930 and 1980, with a figure for the United States of over 26,500km for a similar time period (Brookes, 1985). Channelisation efforts have historically ignored the wider context of catchment coarse sediment dynamics. For example, when the Blackwater River in Missouri, USA, was locally steepened from a gradient of 0.0017 to 0.0031, the channelised reach developed a capacity to transport an amount of sediment far greater than that of its upstream or downstream neighbours. The resultant erosion in the channelised reach caused downstream aggradation to a depth of two metres in 60 years and a consequent increase in flooding (Emerson, 1971). Similarly, Brookes (1988) describes how the widening of British rivers, motivated by misguided attempts to increase flow-carrying capacity, encourages the deposition of sediment. This is because widening has the effect of reducing stream power per unit bed area and therefore sediment transport capacity, so that deposition occurs in the form of berms as the stream attempts to re-establish its own width (Brookes, 1988).

Many historic, and indeed, contemporary approaches to river management use simplified models of fluvial coarse sediment dynamics such as Lane's stable stream balance (Lane, 1955b) and Schumm's river metamorphosis (Schumm, 1969). The development of these, and other, 'tools' will be explored in Section 2.5.

The need for an understanding of coarse sediment dynamics within British river management has become imperative over recent decades due to a combination of: i) a shift in the way that contemporary society views human interaction with natural systems; and ii) anthropogenic and natural changes to the driving influences behind fluvial-sediment interactions. The next two sections examine how these two factors have heightened the importance of understanding coarse sediment dynamics within British river system management. Whilst this thesis is primarily focused on the implications of coarse sediment dynamics for the management of British rivers, due to a relative paucity in academic literature detailing British river management schemes, examples have often been drawn from elsewhere.

2.2 Contemporary shifts within the management of British rivers

2.2.1 River channel management – from controlling, to working with, natural processes

An increasing population within the British Isles, and many other nations, has led to severe demands being made on contemporary natural environments (Newson, 1992). Rivers are fundamental components of the environment and increasing developmental pressures, along with the antecedent influence of historic resource needs, have driven ever-rising levels of anthropogenic interaction with the fluvial environment. Whilst evidence of human management of British river channels, in the form of weir control structures for fishing, has been recorded from Anglo-Saxon times, it is from the industrial revolution in the eighteenth century onwards that human society has sought increasing demands from the fluvial system (Newson, 1992). Technological advances made during the industrial revolution unleashed the powerful notion that nature could be conquered and its resources utilised and exploited for the benefit of humanity (Downs and Gregory, 2004). The founding statement of the Institute of Civil Engineers in 1830 illustrates this ideological stance: *"to harness the great sources of power in nature for the use and convenience of man"* (cited in: Downs and Gregory, 2004). As a result, human activities progressively moved away from a traditional avoidance of the near-river floodplain towards increased utilisation of river channels for navigation and power generation and an increased occupation of floodplains by settlements and industry. To facilitate this increased occupation, those responsible for river management attempted to eliminate the threat of flooding *via* the engineering of river channels. In fact, until relatively recently, Britain's entire river management strategy was dominated by dam construction, channelisation and river diversions to satisfy power, navigation, and water supply requirements whilst attempting to prevent river flooding (Downs and Gregory, 2004). This tendency towards management approaches that stifle natural fluvial action has been characterised by the slogan *"technology can fix it"* (Leopold, 1977: 429).

This management approach was neither wholly successful or sustainable. Due to its failure to accommodate the natural tendency for the river channel to evolve over time by eroding and transporting the coarse sediment comprising its boundaries, channelisation efforts have often been perceived to fail outright (Downs and Gregory, 2004). In fact, in many cases, adverse indirect reactions occurred, involving unforeseen river channel changes that were prompted by the original 'solution'. The Lower Mississippi River, USA is a clear example of the problems that can result from a failure to consider coarse sediment dynamics within an engineering 'solution'. Straightening of the river for navigational and flood protection purposes created steepened reaches with a high capacity for erosion, resulting in nick-point migration upstream along the main river channel and its tributaries (Smith and Winkley, 1996). Along with the problems that arose directly from excessive erosion upstream of the straightened reaches, the resultant overload of sediment delivered downstream choked the channel, disrupting its navigational function and flood conveyance capacity. All of these consequential issues have required further difficult river management decisions to be made by the authorities responsible for the Mississippi in order to both satisfy the needs of human activities along the river and avoid further disruption of the natural sediment system. Similar responses, although on a smaller scale, have been observed as a result of channelisation projects on British rivers where river managers failed to appreciate the natural dynamics of fluvial systems that result from the transfer of the coarse sediment comprising channel boundaries. For example, in response to flooding problems in the lower reaches of Mimmshall Brook in Hertfordshire those responsible for river management in the 1950s performed a series of flood control measures (Sear, 1992). These measures included widening the channel and raising the banks with the excavated spoil. As a result of the consequent loss in transport capacity the channel has subsequently required maintenance dredging due to the accumulation of gravel shoals within the widened reach (Sear, 1992). Similarly, Brookes (1992) describes another example of this type of situation on the River Cherwell in Oxfordshire where, following an engineered widening in 1967 that did not take into account the channel's low transport capacity, the channel reduced its low flow width through a 14 year period of continued deposition. In a study of the morphological consequences of river channelisation in England and Wales, Brookes (1985) found that downstream of high energy channelised reaches, channels typically underwent erosive adjustment because of an increase in flows exceeding a threshold for the erosion of coarse sediment.

Partly as a consequence of the perceived failure of a river management strategy based on controlling the fluvial system, and partly because of increased environmental awareness, in recent decades river channel management has moved towards a philosophy of 'working with the river rather than against it' (Winkley, 1972). This modern-day philosophy encourages approaches that are designed with consideration of the sediment dynamics operating within the reach, and catchment, in question. Using this philosophy, there has been a proliferation of projects to mitigate and enhance heavily managed river channels, with rivers that were previously straightened and re-sectioned returned to a state approximating their 'natural' condition (Newson, 1992). In order to successfully facilitate this type of 'natural' river channel restoration it is clear that an appreciation for the role of coarse sediment dynamics is necessary. Failure to account for coarse sediment transfer within contemporary river channel restoration projects will potentially lead to problems similar to those that resulted from the hard engineering approaches that they are intended to 'fix'.

Evidence for the importance of accounting for coarse sediment dynamics in river management can be found in the cost of maintaining the design channel dimensions of British rivers. The term 'channel maintenance' describes the structural and dredging operations necessary to maintain a design channel shape because of excess deposition. The annual bill for coarse sediment related river maintenance carried out by all drainage authorities in the United Kingdom exceeded £20 million in 1995 (Sear *et al.*, 1995). Therefore, river management approaches that are sympathetic to the natural sediment dynamics particular to the river in question are vital in minimising the economic cost of channel maintenance. If a channel design can effectively transport sediment with minimal net aggradation or degradation, then a potentially expensive post-project maintenance commitment becomes significantly less expensive, resulting in a more sustainable form of river management (Gardiner, 1998). For this to be achieved in British river management, an appreciation of catchment-scale coarse sediment dynamics is necessary.

2.2.2 Flood risk management – from containing floods to minimising flood risk

Approaches that attempt to limit disruption and damage from flooding have changed significantly in recent years. In Britain, there has been a significant change in emphasis away from a strategy of flood defence, within which it was deemed necessary to attempt to control the river system, towards one of 'flood risk management', which recognises that more 'managed flooding' is both economically pragmatic and essential to meeting goals for biodiversity and to sustain good ecological status in river and coastal systems (Thorne *et al.*, 2007). This change in approach reflects both the future uncertainties in flood prediction arising from climate change, and recognition that continuing to rely on a progressive strengthening of flood defences is no longer tenable in the light of predicted future climate change and socio-economic development (DEFRA, 2005). As a result of this shift, it has become even more important to gain greater understanding of the process of fluvial flooding.

A river floods when main channel water levels are sufficient to exceed local bank height. Therefore, variation in flow magnitude is not the sole control over flood risk since river channel conveyance, the capacity of a river channel to contain a given discharge, also has an important part to play. A great deal of research has centred on the influences of both land management practices, such as land-use change, clear-cutting and urbanisation (O'Connell *et al.*, 2005), and climate change (Cameron *et al.*, 2000; Prudhomme *et al.*, 2003) in influencing the magnitude and frequency of high-flow events. However, these studies are largely concerned with flow magnitude and not the conveyance of the channels themselves. Relatively little attention has been given to the important role of within-channel morphology for flood risk and inundation extent.

Of the research that has focussed on the role of sediment dynamics within flood risk management, the results suggest that increased understanding of the movement and storage of sediment through the river system is needed. For example, on the Skokomish River, Washington State, USA, Stover and Montgomery (2001) used historical data series to show that, whilst flow magnitudes were either reducing slightly or not changing, there was evidence of significant flood stage increases associated with a given discharge. Similarly, Pinter and Heine (2005) used equal discharge analysis on the Lower Missouri river to show that, for given flow magnitudes, water stage levels have systematically risen over recent history. Discharges that were completely in-bank during the early part of the twentieth century were more recently found to lead to flood inundation, with the most extreme floods having a stage up to 3.7 metres higher than at the start of the record. Whilst reduced flow velocities resulting from increased flow resistance was found to be responsible for the increased stages at three of the five stations considered, Pinter and Heine (2005) found that at the remaining two stations the increased flood levels were due to constrictions in channel cross-sectional area resulting from net sediment deposition. Within both of these USA-based studies, the results demonstrate that within channel aggradation can cause reductions in channel conveyance that are significant enough to increase flood risk. This emphasises the importance of considering the impact that coarse sediment dynamics have upon flood inundation.

Lane *et al.* (1997) describe how the general lack of consideration for the role of morphological changes in British flood risk management may be due to the traditional view of sediment delivery as a local, temporary disturbance to equilibrium channel morphology. Within this conventional view it is thought that when excess sediment is delivered, within a relatively short time-span, the channel equilibrium capacity re-establishes itself through transport of that sediment downstream through the river system (Wolman and Gerson, 1977). However, this idealised viewpoint overlooks the capacity of fluvial processes to cause rapid aggradation or degradation over short time periods, even in Britain's relatively low energy river systems. Through numerical simulations of flood inundation on a reach of the River Wharfe in Yorkshire, Lane *et al.* (1997) found that bed aggradation over a 15 month period reduced the conveyable bankfull discharge by 6.1%. The associated increase in flood inundation during flood events demonstrated by Lane *et al.* (1997) illustrates the importance that coarse sediment dynamics can have for flood risk management.

Rapid degradation might optimistically be viewed as agreeable for flood risk management purposes because the associated increase of channel cross-section increases conveyance, lowering the water level for a given discharge. However, channel enlargement can also cause problems for flood risk management. In particular, channel bed degradation can undermine flood defence assets, reducing their effectiveness and increasing the risk of failure under load (Wallerstein and Soar, 2006).

Further, along with the changes in channel cross-section geometry described above, increases in coarse sediment transport capacity can also influence bed material size: more competent flows progressively entrain coarser particles, increasing the average size present on the bed (Hey, 1979). For example, Ferguson and Ashworth (1991) describe how slope-driven changes in transport competence along the Allt Dubhaig in the Scottish Highlands caused dramatic changes in bed material size as a result of hydraulic sorting. Since (at least in rivers where bed material size consists of gravels and cobbles) flow resistance is controlled predominantly by bed roughness (Manning, 1891; Strickler, 1923; Colebrook and White, 1937), variations in bed material size resulting from changes in coarse sediment dynamics consequently impact on flow stages.

Modelling software programs currently used to predict flow stages for flood risk management, such as ISIS, generally treat the channel as a static conduit for the conveyance of water. Representations of channel geometry and flow resistance are kept constant over time, even when modelling flow events representative of future climatic scenarios. Clearly, if river channel morphology and flow resistance both change over time in response to coarse sediment dynamics, the application of a static channel condition when modelling future events will lead to significant uncertainty concerning the model's predictive capabilities.

If the management of flooding within British rivers is to effectively shift from simply containing floods using engineered structures, to minimising the risk associated with flooding, then there needs to be an appreciation of the effects of coarse sediment dynamics. Failure to account for sediment may result in the destruction of existing flood defence infrastructure, reduction in conveyance of river channels, and erroneous strategic decisions based upon inaccurate predictions of future flood stages.

2.2.3 River habitat restoration – from neglecting to restoring river habitats

Along with driving the move towards a risk-based approach to flood management, contemporary shifts in river management policy in Britain have also elevated the status of ecology and the 'river habitat' in the fluvial environment. The main driver for this change has been an increase in the value that society attaches to the natural environment (Downs and Gregory, 2004). A general increase in environmental empathy has led to political recognition of the importance of improving the ecological status of British rivers, evidenced by the formation of the Environment Agency and development of the River Habitat Survey. More recently, international legislation, in the form of the European

Union's Water Framework Directive (EU, 2000), has driven a major shift towards the consideration of ecological sensitivity in British river management.

It is recognised that river sediment dynamics play an important role in determining the structure of both the river and its ecosystem (Harper and Everard, 1998). Disruption to these dynamics can deliver potentially polluted sediments to rural floodplains and urban areas, and damage valuable aquatic, riparian and floodplain habitats (Thorne *et al.*, 2004). The influence that sediment dynamics have on ecological quality can arise in two ways, both through the impact that excessive fine sediment delivery has on the health of in-stream biology, and also through the influence of degraded morphological structure on physical habitat quality and diversity.

Hendry *et al.* (2003) described the first of these impacts, explaining how the increased sediment loads resulting from intensification of agricultural practices have had a deleterious impact upon river habitat in British rivers. Soulsby *et al.* (2001) further demonstrated this type of impact in their study of salmonid spawning on a reach of Newmills Burn, a small, canalised, lowland tributary of the River Don in Aberdeenshire. They found that, canalisation and intensive cultivation had seriously degraded the physical habitat in the lowland stream in comparison to conditions in undisturbed, upland tributaries. Of particular importance was infiltration of fine sediment into the open gravel matrices, which resulted in egg mortality rates as high as 86% in the Newmills Burn (Soulsby *et al.*, 2001).

Hendry *et al.* (2003) also identified that the landscape-scale land drainage performed to increase the area available for cultivation has profoundly impacted the ability of British watercourses to support salmonids. This happened because land drainage increased runoff and stream power, causing an increase in erosion, stream widening and instability that reduced physical habitat quality in many British rivers. An American example of this latter influence is described by Shields *et al.* (1998) who identified some of the major ecological impacts caused by sediment imbalance in the incised streams of the Yazoo Basin, Mississippi. There, fluvial instability caused rapid channel incision and widening, resulting in reduced spatial habitat heterogeneity, accentuated flood peaks, reduced stream-floodplain interaction, and the removal of low-velocity refugia.

The importance of sediment dynamics to in-stream habitat creation is recognised by Rice *et al.* (2001) in their model demonstrating the effects that shifts in hydrology and sedimentology can have on the presence and absence of lotic fauna within river networks. As bed sediment character changes at tributary confluences and other sediment recruitment points, this influences physical habitat structure and, therefore, the longitudinal organisation of macroinvertebrate benthos (Rice *et al.*, 2001).

The transfer of coarse sediment within the fluvial system exerts an important influence over physical habitat structures within rivers which, in turn, are a key control over river ecology. It follows that successful improvement of in-stream ecology depends on understanding coarse sediment dynamics within the fluvial system. Recognising this, Downs and Gregory (2004) argued that the restoration of natural sediment transfer regimes should be a priority when attempting to improve in-stream habitat and/or ecology. Downs and Gregory (2004) provide a template for river habitat restoration projects in the form of a hierarchy of management principles within which the preservation and restoration of natural flow regimes and coarse sediment transfer pathways rank above the creation of physical habitat structures, which in turn rank higher than the introduction of aquatic flora and fauna. This is because, for instance, attempts to restore ‘natural’ channel habitat are unlikely to be sustainable without attention to the proper functioning of the coarse sediment transfer regime that interacts with fluvial processes and drives morphological adjustments. Similarly, restoring the riparian plant community in a highly channelised reach is unlikely to succeed unless sediment dynamics have already been addressed because the channel will lack the appropriate physical habitats (Downs and Gregory, 2004). In summary, without an appropriate understanding of the nature of coarse sediment transport in British rivers, many habitat restoration schemes are likely to be unsustainable. However, it must be noted that, despite the importance of physical stressors such as sediment status, seemingly ideal physical conditions do not necessarily guarantee ecological richness and diversity (Ormerod, 2004).

2.2.4 Integrated catchment management

River basins are ideal planning units for integrated approaches to the management of natural resources and hazards because they are clearly bounded, physically functional, hierarchical in scale and culturally meaningful (Newson *et al.*, 2000). Water resource provision, flood control, navigation, agricultural provision, recreation and erosion control each require careful management in British river catchments. Dealing with each of these resource demands separately is not only inefficient, but also potentially self defeating since they are inter-linked and, therefore, frequently either align or conflict with each other. Consequently, since the end of the nineteenth century, there have been increased efforts to move towards integrated catchment management. However, despite this, a review of 21 different approaches to 'integrated basin management' by Downs *et al.* (1991) demonstrated that consideration of the morpho-dynamics of the fluvial system was missing from the majority. Clearly, the processes mobilising coarse sediment and the consequent temporal modifications of channel morphology are important components of the fluvial system. The transfer of coarse sediment through river catchments also has important implications for: water resource provision (through reservoir sedimentation); flood control (through reduction in channel conveyance capacity due to siltation); navigation (through the development of in-channel depositional features); and erosion control (through channel scour). In turn, aspects of catchment management are important for the transfer of coarse sediment in British rivers (Walling, 1999). Activities such as mineral extraction, cultivation, urbanisation, afforestation and deforestation have been shown to affect the intensity and spatial distribution of erosion and sedimentation in catchments, often modifying sediment yields and instigating both up- and down-stream morphological responses. Because of this interaction, it has been argued that coarse sediment dynamics should be directly considered within any truly integrated catchment management approach (Brookes, 1995).

The bodies responsible for the management of British river catchments have recently begun to recognise the importance of coarse sediment dynamics within integrated catchment management approaches. This is demonstrated clearly in the Environment Agency's Catchment Flood Management Plans (CFMPs) which, *"consider sediment dynamics…because maintaining how these processes function throughout the catchment is critical to achieving both sustainable flood risk management, and a diverse and healthy river in terms of habitats and ecology"* (EA, 2008: 41). Policies are now in place which provide the strategic framework necessary to incorporate geomorphology into integrated catchment management. Indeed, much of the activity and input from geomorphology is now directed towards the strategic planning and management of rivers, along with the inputs into river engineering (Hooke, 1999). Despite increased recognition of the importance of geomorphology and sediment dynamics to integrated catchment management, tangible evidence of geomorphological analysis within strategies such as CFMPs remains limited. As such, treatment of coarse sediment dynamics within British integrated catchment management is in a paradoxical state whereby sediment dynamics are acknowledged as being of vital importance, though practical consideration for them is limited (Lewin and Longfield, 2010). This state of affairs reflects a combination of limited budgets and the relatively high expense of applying existing tools for analysing sediment dynamics at the catchment-scale - issues explored further in Chapter Three.

2.3 Contemporary shifts in catchment process drivers

Alongside recent shifts in the manner in which responsible bodies view their duty to manage catchments and river environments, there have also been important changes to the key drivers controlling the fluvial system, notably catchment land-use and climate. Changes to these drivers are predicted to continue into the foreseeable future, and may drastically influence catchment sediment dynamics (Lane and Thorne, 2006). These changes: past, present and predicted, have heightened the need to understand, and to predict, coarse sediment dynamics in river systems so that future catchment management strategies can be determined appropriately.

2.3.1 Climate change

One of the key elements affecting the hydrological, and consequent geomorphic response, of a catchment is climate. Relatively modest climatic changes can trigger major episodes of fluvial adjustment (Coulthard *et al.*, 2005). Consequently, forecasted global climate change scenarios that predict an increased frequency of heavy rainfall and rising sea-level could have major implications for coarse sediment dynamics. Changes in the amount, seasonality and intensity of precipitation will result in changes in channel flow characteristics which, in turn, will impact coarse sediment transfer. Although there is uncertainty concerning how changes in precipitation covert to changes in flood hydrology, observations that both: i) rainfall intensity; and ii) the frequency of high intensity rainfall have increased in Britain, mean that river management agencies must take note of the impact that predicted climate change may have on coarse sediment dynamics (Lane *et al.*, 2007).

Reid *et al.* (2007) applied predicted climate change scenarios to a coupled hydrology-sediment delivery model. They found that, by the 2080s, predicted changes in climate may increase sediment delivery from a sub-catchment of the River Wharfe by between 28% and 68% depending on the precipitation scenario selected. This modelling emphasises that coarse sediment dynamics in British rivers are likely to be strongly affected by predicted climate change because of increased erosive power of run-off in the headwaters delivering higher quantities of sediment downstream through the catchment. In the light of these findings, tools for understanding and predicting catchment-scale coarse sediment dynamics are important in planning adaptations to future climatic change.

2.3.2 Land use change

Over the last 2000 years, human activity in Britain has had an increasing influence on the manner in which drainage basins respond to hydrological inputs.

In fact, Knighton (1999) argues that this human modification of the physical environment may have induced changes similar in scale to those produced by large climatic changes in the distant past. Results from erosion plots and catchment experiments in many different areas of the world have shown that land use change can have significant effects on both erosion rates and the sediment yield of rivers (Walling, 1999). Vegetation cover is an important control on both catchment hydrology and sediment and is extremely susceptible to human disturbance. A long history of forest clearance for agricultural land use in Britain has led to accelerated soil erosion on hill-slopes and a consequent increase in the amount of sediment supplied to streams, dramatically influencing the sediment dynamics of British rivers (Henshaw, 2009).

At the beginning of the twentieth century, the United Kingdom Forestry Commission was established with the remit to plant fast-growing non-indigenous conifers, both to provide a national timber resource and to protect upland catchments from pollution and soil erosion. However, in order to provide open drainage ditches for the planted trees the natural surface vegetation was cleared. This removal of natural protection exposed the vulnerable material beneath and resulted in significant erosion and increased delivery of sediment into the fluvial system (Newson, 1980; Leeks and Marks, 1997).

A further disruption to sediment yields in recent years has resulted from agricultural intensification which has produced a large increase in the stocking density of grazing animals (Henshaw, 2009). Research in the Afon Einon test catchment in the upper reaches of the Severn basin has revealed that intensively grazed soils become less permeable through top soil compaction, drastically altering the hydrograph of the river system. Preliminary results have shown this to have significant impacts on sediment transfer through the catchment, emphasising the importance that land-use changes have, not only on sediment delivery to river channels, but also on the river's capacity to transport coarse sediment (Henshaw, 2009).

Alongside these agriculturally-based land use changes, the effects of continually rising levels of urbanisation within Britain on catchment hydrology also have important geomorphological impacts. For example, from an extensive survey of urbanised catchments in Britain, Roberts (1989) identified that, on average, channels were enlarged by a factor of 1.61 in response to the increased frequency and magnitude of flood discharges resulting from urbanisation.

The impact that catchment land use changes have had, and will likely continue to have, on coarse sediment dynamics increases the potential for British river systems to experience significant sediment management issues. A variety of academic studies have indicated that, as a result of land use change, there is a trend towards catchments experiencing increased sediment delivery to channels and an accelerated hydrological response, resulting in increased transfer of sediment loads throughout impacted river systems (Newson, 1980; Roberts, 1989; Leeks and Marks, 1997; Walling, 1999; Henshaw, 2009). It is imperative that the managers of British rivers have a means of assessing coarse sediment transfer at the catchment-scale in order to deal effectively with these changing systems.

A further argument made by Lane *et al.* (2007) is that the two contemporary driver changes identified above may interact. Specifically, shifts in land management practices have the potential to sensitise river basins to the effects of climate change. Indeed, Macklin and Lewin (2003) identified that, as a result of historical land use change from woodland to agricultural grassland, British river basins are now more sensitive to climatic fluctuations than they were previously. This is supported by the modelling efforts of Coulthard and Macklin (2001) who, using the cellular landscape evolution model CAESAR, have demonstrated that there is a strong, non-linear interaction between climate change and historical land use changes and how they impact on sediment dynamics in river catchments. Therefore, given the potentially dramatic impacts that the combined effect of future land use and climate changes may have on the sediment dynamics of British rivers, it seems prudent that catchment managers have tools appropriate for assessing coarse material transport and transfer in the fluvial system.

2.4 A role for fluvial geomorphology: the importance of understanding coarse sediment dynamics at the catchment-scale

As identified above, engineering works and management actions that fail to account for sediment dynamics risk disrupting sediment transfer in the fluvial system, triggering new patterns of erosion and sedimentation that require increased maintenance, further engineering interventions, or both, resulting in adverse environmental consequences. Also, sediment impacts associated with channel instability are seldom confined to the disturbed reach but often extend throughout the river network in both the up- and downstream directions (Simon, 1989). For example, destabilisation of adjacent downstream reaches can occur through siltation due to the transmission of additional sediment, whilst upstream reaches may be affected by nick-point migration as the system adjusts towards an equilibrium long-profile (Hey, 1979; Simon, 1989). Darby and Thorne (1992) described how channelisation of the Mimmshall Brook, Hertfordshire started a process of nick-point migration upstream of the managed reach, causing bed degradation and increases in bank height, the sediment delivery from which subsequently led to the infilling of swallow holes downstream of the managed reach. Connectivity within the fluvial system means that morphological responses to any system inputs at any given location can be transmitted over long distances. Therefore, within river channel design it is necessary to use catchment-wide approaches to underpin effective regional sediment management.

As a result of the contemporary changes described above, the importance of accounting for coarse sediment dynamics within river management has become increasingly recognised within the river management literature. A review of papers published over the last two decades produced an extensive collection of articles that identify links between coarse sediment dynamics and river management. A selection of these articles is detailed in Table 2.2. As described earlier in this chapter, and as is evident from Table 2.2, the relationship between coarse sediment dynamics and human activities has a two-way causal linkage: coarse sediment dynamics can have impacts that are of concern to those managing the fluvial environment (Gilvear, 1999; Hooke, 1999; Newson and Newson, 2000; Kondolf *et* *al.*, 2001; Stover and Montgomery, 2001; Thorne *et al.*, 2004; Gob *et al.*, 2005; Lane *et al.*, 2006; Newson and Large, 2006; Eyquem, 2007; Lane *et al.*, 2007; Baldigo and Warren, 2008; Raven *et al.*, 2009; Vaughan *et al.*, 2009; Miller and Kochel, 2010); while river management actions can perturb the transfer of sediment through the fluvial system (James, 1999; Schmidt *et al.*, 2001; Stott and Mount, 2004; Downward and Skinner, 2005; Harmar *et al.*, 2005; Hudson *et al.*, 2008; Wishart *et al.*, 2008; Burroughs *et al.*, 2009; Ronco *et al.*, 2010). In practice, human interventions can have such a dramatic impact on coarse sediment dynamics that the resultant response in the fluvial system forces further management actions to be taken (Hudson *et al.*, 2008).

Evidence of the increased importance of sediment related problems within river management can be found by analysing recent trends in academic publications. Analysis of journal articles published over the last two decades shows that while the number of journal articles related to 'river management' increased by a factor of ~15 between 1991 and 2009, the number of journal articles related to 'river sediment management' increased by a factor of ~28 during the same period (Figure 2.1). These results indicate a trend for sediment-related concerns becoming a higher priority within academic studies of river management.

Table 2.2 Examples of academic journal articles documenting the relevance of coarse sediment dynamics within river management

Reference	Key Issue	Findings
(Gilvear, 1999)	Importance of coarse sediment dynamics within engineering projects	Application of geomorphological principles should be pro-active rather than reactive within all types of river engineering project.
(Hooke, 1999)	Importance of coarse sediment dynamics within engineering projects	Coarse sediment dynamics increasingly represented within river management policy and practice in the UK, but recent developments in the appreciation of complexity and feedbacks within geomorphology still require integration.
(James, 1999)	Impact of hydraulic mining on coarse sediment dynamics	Historic hydraulic mining has had both an immediate and long-term impact upon channel morphology and stage-discharge relations on a collection of rivers in Sierra Nevada.
(Newson and Newson, 2000)	Importance of coarse sediment dynamics for habitat	Spatial pattern of biology in river channels is dependent on longitudinal zonation and physical biotopes driven by coarse sediment dynamics.
(Kondolf *et al.*, 2001)	Importance of coarse sediment dynamics within restoration projects	River restoration project in California failed because of a failure to appreciate the processes that determine channel form, notably coarse sediment dynamics.
(Schmidt *et al.*, 2001)	Impact of dam release flows on coarse sediment dynamics	Relatively large controlled flood within the impoundment regime on the River Colorado re-worked sediment comprising channel boundary, temporarily increasing habitat diversity.
(Stover and Montgomery, 2001)	Importance of coarse sediment dynamics for flood risk management	Progressive reduction of channel conveyance indicated that increased flooding on the River Skokomish, Washington resulted from aggradation without an increase in peak discharges.
(Stott and Mount, 2004)	Impact of land-use change on coarse sediment dynamics	Coniferous forest plantation generates downstream waves in coarse sediment. These waves are thought to be responsible for channel instability in lowland reaches of afforested UK catchments.
(Thorne *et al.*, 2004)	Importance of coarse sediment dynamics for flood risk management	Improvements were made to the flood defence infrastructure of the Hawkcombe Stream by accounting for coarse sediment dynamics using a qualitative fluvial audit and 1-D modelling of flow and sediment with ISIS Sediment.
(Downward and Skinner, 2005)	Impact of mills on coarse sediment dynamics	Failure of unmaintained mill structures in UK rivers can lead to a local increase in bed slope that causes the upstream migration of a nick-point.
(Gob *et al.*, 2005)	Importance of coarse sediment dynamics on for flood risk management	Attempts to increase river channel conveyance via an intensive dredging regime on the River Semois in Belgium had limited impact due to rapid infilling of the channel with coarse sediment transported from upstream.
(Harmar *et al.*, 2005)	Impact of channelisation on coarse sediment dynamics	Local steepening of the long profile of the Lower Mississippi River impacted coarse sediment dynamics, which, because of planform containment, resulted in phases of aggradation and degradation and changes in cross-sectional form.
(Lane *et al.*, 2006)	Importance of coarse sediment dynamics for flood risk management	Modelled increases in coarse sediment transfer in the River Wharfe resulting from changes in precipitation associated with climate change cause sedimentation that has a greater impact on flood inundation than the predicted changes in hydrology.
(Newson and Large, 2006)	Importance of coarse sediment dynamics for habitat	Geomorphological condition, driven by coarse sediment dynamics, plays an important role within the 'natural health' of river systems that the EU's Water Framework Directive is aiming to improve.
(Eyquem, 2007)	Importance of coarse sediment dynamics for catchment-scale management	Coarse sediment dynamics link the physical function of the river to its ecological status. As a result, fluvial geomorphology can be successfully applied to inform river basin management.
(Lane *et al.*, 2007)	Importance of coarse sediment	16 months of measured in-channel sedimentation in an upland gravel-bed river cause about half of the increase in

	dynamics for flood risk management	inundation extent that was simulated to arise from 50 years of climate change.
(Baldigo and Warren, 2008)	Importance of coarse sediment dynamics for habitat	A restoration design that took into account coarse sediment dynamics and converted channelised rivers in the Catsgill Mountains, New York into naturally functioning rivers resulted in community richness and biomass increasing by more than one-third.
(Hudson *et al.*, 2008)	Impact of channelisation on coarse sediment dynamics	Flood management on the Lower Mississippi and Rhine rivers initiated positive feedbacks with unintended geomorphic consequences for coarse sediment dynamics that require further management options to minimize flood risk.
(Wishart *et al.*, 2008)	Impact of gravel extraction on coarse sediment dynamics	Gravel extraction from the River Wear causes a local disturbance to coarse sediment dynamic and can result in knick-point incision. Management strategies to prevent incision merely maintain the disturbance, and delay the inevitable morphological adjustment.
(Burroughs *et al.*, 2009)	Impact of dam removal on coarse sediment dynamics	Following the removal of a dam from the Pine River in Michigan, sediment fill incision resulted in a narrower and deeper channel upstream, with higher mean water velocity and somewhat coarser substrates. Downstream deposition resulted in a wider and shallower channel, with little change in substrate size composition.
(Raven *et al.*, 2009)	Importance of coarse sediment dynamics for flood risk management	Over a six-year monitoring period, the mean bed level in the Upper Wharfe rose by 0.17 m with a maximum bed level rise of 0.5 m noted at one location over a five month winter period. These rapid levels of aggradation have a profound impact on the number and duration of overbank flows with flood frequency increasing on average 2.6 times and overbank flow time increasing by 12.8 hours.
(Vaughan *et al.*, 2009)	Importance of coarse sediment dynamics for habitat	A major research priority is to identify pattern among organisms, ecological functions and river hydromorphological character in order to understand the ecological importance of hydromorphology as prescribed by the EU's Water Framework Directive.
(Miller and Kochel, 2010)	Importance of coarse sediment dynamics within restoration projects	Restoration of river channels in North Caroline without properly accounting for coarse sediment dynamics resulted in large post-construction adjustments within highly dynamic stream channels characterised by a combination of high sediment transport capacity, large sediment supply, and/or easily eroded bank materials.
(Ronco *et al.*, 2010)	Impact of dam construction on coarse sediment dynamics	Construction of a dam on the Lower Zambezi River inhibited coarse sediment transfer to the lower reaches of the river system, causing a temporary erosion of its delta.

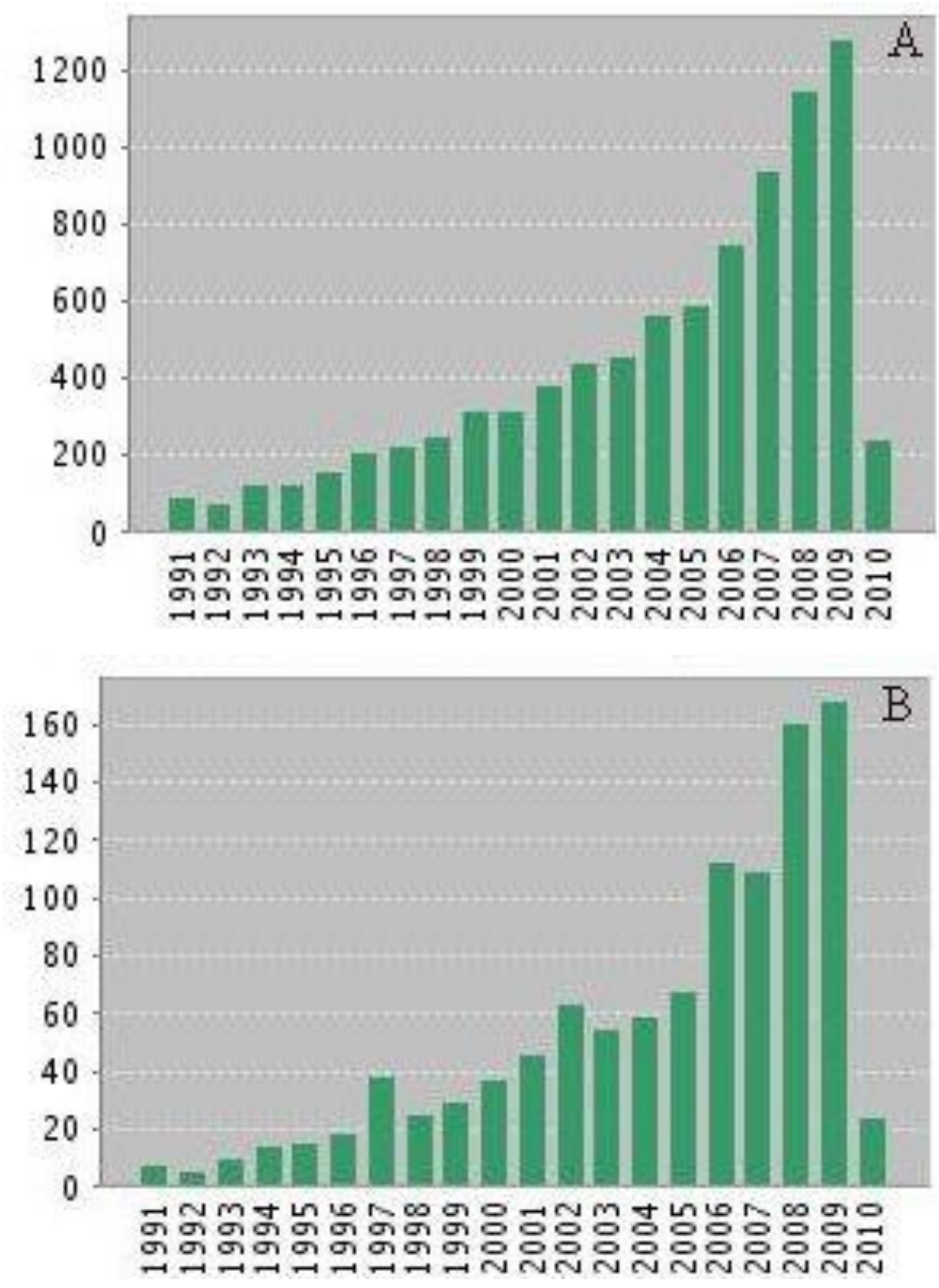

Figure 2.1 Web of Science citation reports containing the number of articles published each year from 1991 to 2010 within the topics: (A) 'river management'; and (B) 'river sediment management'. Taken from ISI Web of Knowledge 10th April 2010.

This trend is both a reflection of, and reflected by the policies set out by the agencies responsible for the strategic management of British rivers. Sediment-related management has been becoming increasingly recognised within these authorities and, during the past three decades, application of the principles of fluvial geomorphology has been recognised as a vital component for effective river management in Britain (Brookes, 1995; Hooke, 1999). The Environment Agency (1998) set out a coherent approach to the application of fluvial geomorphological principles to river management. Their framework involves a sequential decrease in spatial scale through the initial stages of a river study whereby a ‘catchment baseline survey’ and project level ‘fluvial audit’ are performed first, to provide the information necessary to classify the river system in terms of spatial influences and temporal changes, and to prioritise reaches for further investigation (Sear *et al.*, 2010). These studies attempt to address the nature of instability within the system prior to undertaking a more detailed geomorphological assessment of the flow and sediment regime supplying the project reach and identifying site constraints which would influence the final design.

It is considered here that these trends in the representation of sediment-related issues by both academics and policy makers is a direct result of those changing management attitudes and process drivers explored in Sections 2.2 and 2.3. Yet, despite the recent increase in recognition for the importance of fluvial geomorphological principles in river management, further advances are necessary. Thorne *et al.* (2004) identified how operational research is urgently required to develop analytical tools capable of identifying reaches vulnerable to morphological destabilisation in order to provide the basis for river management that is pro-active rather than responsive. They demonstrated an example of this pro-active consideration for morphological response in the redesigning of a flood management scheme on the Hawkcombe Stream in Somerset. In this case, the key issue that needed to be addressed was sedimentation in a culvert beneath the settlement of Porlock, reducing the standard of flood defence. To adequately account for sediment dynamics within the system, a sediment transport analysis was performed using both qualitative and quantitative elements. The combination of these tools enabled modelled predictions of sediment processes through the reach for various scenarios so that informed decisions regarding the most appropriate management option for the stream could be made (Thorne *et al.*, 2004).

This type of pro-active consideration for coarse sediment dynamics is necessary for effective river management. Given the contemporary shifts in both river management paradigms and catchment process drivers explored above, it is vital that scientifically robust and practically useful tools that account for coarse sediment dynamics at the catchment-scale are available. However, despite fluvial geomorphology now being formally incorporated into strategic planning frameworks (Hooke, 1999), there is still limited substantive analysis of coarse sediment dynamics within British river management. Treatment of coarse sediment dynamics within British integrated catchment management is in a transitional state whereby it is acknowledged as being of vital importance, and yet practical consideration for it is limited. It is thought that the primary cause of this condition is that existing tools either lack scientific credibility or the practical utility necessary to meet most management needs. It is considered here that the main factor limiting the application of most existing approaches is non-availability of the data necessary to apply them at the catchment-scale. Both the availability of data on British rivers; and the strengths and limitations of the existing approaches are explored further in the next chapter, in order first to confirm the validity of this hypothesis and second to inform the development of a new approach that accounts for catchment-scale coarse sediment dynamics. However, before any thought is given to the development of new approaches, due consideration must be given to past research. Therefore, to provide a grounding for the theoretical issues addressed within this thesis, the remainder of this chapter will review past strands of research that have contributed to our current understanding of how coarse sediment dynamics influence river channel morphology.

2.5 A review of attempts to explain the influence that coarse sediment dynamics have on river channel morphology

2.5.1 Introduction – a brief retrospective on explanatory approaches within fluvial geomorphology

The insights gained by closely examining our past can provide the most enlightening view of our present and our science

(Richards, 1995: 123)

Contemporary attempts to understand and explain coarse sediment dynamics in natural river systems are contained within the field of fluvial geomorphology, which is broadly defined as the study of the interactions between river channel forms and processes (Charlton, 2008). Whilst early treatment of the subject matter now addressed by fluvial geomorphology was undertaken by a mixture of geologists, engineers and potomologists, for the purposes of this review these scientists will be referred to as fluvial geomorphologists. Understanding how fluvial geomorphologists have previously attempted to understand coarse sediment dynamics provides a useful background for the satisfaction of the aims of this thesis as history can be used to *"furnish context and perspective for the current status of an academic discipline"* (Sack, 2002: 318).

The discipline of geomorphology grew out of the 19th century quest to understand the history of Earth and resulted in the earliest geomorphological models hypothesising how landscapes might generally evolve by erosional development (Chorley *et al.*, 1964). This initial mode of explanation, which is indelibly linked to the work of William Morris Davis, focused on progressive changes in the landscape through time and is usually described as the *evolutionary approach* to geomorphology (Chorley *et al.*, 1973).

However, a small number of fluvial geomorphologists, working at a similar time to Davis, were pursuing systematic, physically-based studies of the processes at work in the landscape, either as fundamental research or in pursuit of practical ends. The findings of these earth scientists were largely dismissed by those following the more established, evolutionary approach to geomorphology. Tensions between the two schools of thought are characterised by one particular exchange between Davis, and Exner, a Viennese physicist who had published experiments on the forced meandering of a stream in a sand flume (Clifford, 2008). Davis disputed Exner's analogy between a meandering stream and a ball rolling down an inclined trough of concave cross section. Exner, in reply, was: *"...sorry that he does not perceive the differences between vague and general knowledge and mathematical expressions which give qualitative results."* (1924: 504; cited in Clifford, 2008). This debate reveals the incongruity between the rising use of laboratory science, through which generality was achieved through controlled experimentation underpinned by simplified physical analogies, and the then dominant evolutionary approach, according to which the complexities inherent to landforms and landscapes had to be addressed and explained by deductive ingenuity. Arguably, the most prominent among the new physically process-based scientists was the American geologist Grove Karl Gilbert. Whilst his approach to fluvial geomorphology did not prevail within his own generation, the *functional approach* it pioneered is recognised as the precursor to approaches adopted during the second half of the 20th century (Church, 2010).

It was recognised by some fluvial geomorphologists (including Gilbert) that a purely empirical approximation of the processes responsible for shaping the Earth's surface was inappropriate (Clifford, 2008). This realisation saw the rise of *systematic analytical representations* of the alluvial channel systems that attempted to represent theoretical understandings of the fluvial system within sets of limiting differential equations.

In contrast to those attempting theoretically-based, analytical representations of the alluvial system, an essentially empirical alternative to the Gilbertian line of reasoning was Kennedy's (1895 cited in Clifford, 2008) theory and practice of stable canal design. Large scale and highly bureaucratised civil water works in India had created a huge natural data-producing laboratory (Blench, 1957). *Regime theory* developed through experience gained from successive attempts to design stable irrigation canals in the Indian sub-continent that led to quantitative, but essentially empirical, 'laws' of channel self-formation (Clifford, 2008).

While regime channels were designed and built by British engineers, American canals were concurrently being designed as *threshold channels* based on the *tractive force theory* for sediment entrainment. This treatment of coarse sediment dynamics differs from regime theory in that it attempts to avoid the possibility of problems associated with scour and siltation encountered in canals with mobile boundaries by ensuring that the forces exerted on the bed and banks never exceeded the values necessary for entrainment.

The release of 'Hydraulic Geometry of Stream Channels and some Physiographic Implications' (Leopold and Maddock, 1953) heralded functionalist approaches as a means of explanation within fluvial geomorphology. It represented as much a strategic document aimed at changing the philosophy and practice of an academic discipline as it did a technical contribution to the literature on water resources (Clifford, 2008). Whilst it was largely informed by the regime theory developed and applied to canal design, it was firmly rooted in the field of fluvial geomorphology, in that it attempted to understand the processes controlling natural channel form. Nevertheless, the authors distanced themselves from the preceding evolutionary approach of fluvial geomorphology of W. M. Davis, commenting that this, *"…classically treated almost exclusively in a qualitative manner…supported by intricately developed general arguments, rather than field data"* and explaining that *"…it would be desirable to analyze some of the concepts quantitatively"* (Leopold and Maddock, 1953: 1). In fact, the concepts expounded by Leopold and Maddock, and later built on by Leopold *et al.* (1964) so dominated thinking at the time that they were deemed by many to mark the final passage into the modern era of fluvial geomorphology (Petts, 1995). This modern era's basic tenet was rooted in Gilbert's (1877) functionalist concept of 'dynamic equilibrium', a condition in which landforms are adapted to the dominant exogenous forcing so that form is maintained through time (Hack, 1960).

A focus on the forms and processes responsible for dynamic equilibrium led to geomorphological thinking becoming predominantly concerned with decennial to centennial time-scales , within which the state of the alluvial system remained relatively steady (Church, 2010). A number of key publications by Stanley A. Schumm and others helped to refine this generally accepted notion of landscape stability. Schumm's *Fluvial System* (1977) included an appreciation for thresholds and dynamically metastable states and made important contributions to the understanding of the time-scales over which different geomorphological processes dominate landform stability and evolution.

However, challenges to the concept of dynamic equilibrium in fluvial geomorphology began during the 1980s, gathering momentum in the 1990s (Church, 2010). These challenges spring from advances that are both conceptual and technological. Major influences include (i) improved technologies for remote sensing and surveying of forms and features at the Earth's surface; (ii) the advent of computers and of massive computational power; and (iii) important developments of absolute dating techniques (Church, 2010). These technical innovations have enabled new generations of analytically-minded researchers to gather large datasets and manipulate them in ways previously unimaginable, stimulated by substantive past and contemporary development of central importance to the discipline, including, for example, demonstration of the importance of non-linearity in relationships between fluvial forms and processes. As a result, many fluvial geomorphologists are now concerned with understanding the impacts of *complex, non-linear dynamics* within Schumm's *fluvial system*.

In the 21st century, the wide availability of considerable computational power in desk-top computers, together with easy access to data via the world-wide web, has made computation beyond the level of simple analytical calculations a natural extension of everyday thinking about problems in fluvial geomorphology. This technological advance has enabled geomorphologists to construct *computational models* of geomorphological systems – models that begin to encompass some of the actual complexity of real landscapes recognised by dynamic systems theory and to allow hypotheses concerning fluvial processes and landscape development to be tested not only rigorously but also routinely.

The remainder of this section (Section 2.5) considers how each of the historical modes of explanation developed within fluvial geomorphology accounted for the impact of coarse sediment dynamics on river channel form. The primary aim of this exercise is to inform development of a new approach for accounting for catchment-scale coarse sediment dynamics. Examples of the interrelationships explained by each mode of explanation are used to illustrate first, the spatio-temporal scale and, second, the level of complexity at which the influence of coarse sediment dynamics on channel morphology were represented.

2.5.2 The evolution of landforms

William Morris Davis's 'geographical cycle' (1899 cited in Chorley *et al.*, 1973) was the first modern theory of landscape evolution. It assumed that uplift takes place relatively quickly and then geomorphic processes, without further complications from tectonic movements, gradually wear down the raised topography. As a result of this denudation, Davis claimed that slopes within landscapes decline through time, reducing topographic features little by little. Eventually, a final extensive flat region close to base level is formed, referred to as a 'peneplain' (Davis, 1902 cited in Chorley *et al.*, 1973). Davis interpreted this reduction process as forming a time sequence of landforms that progress through the stages of youth, maturity and old age.

Davis's cycle of erosion was concerned primarily with processes operating over 'geological' time-scales, during which specific alluvial channel forms were considered to be indeterminate (Schumm and Lichty, 1965). Time, geology and climate were considered to be the independent, controlling variables that influenced vegetation, palaeo-hydrology and, importantly, relief. In turn, palaeo-hydrology and relief influenced valley dimensions. At the time-scales considered in the geographical cycle, little can be discerned regarding the processes responsible for sediment erosion, transfer and deposition within the fluvial system, or the morphologies that sediment dynamics generate. In fact, one of Davis's most faithful supporters, Nigel Fenneman, stated that:

...the cycle itself is not a physical process but a philosophical conception. It contemplates erosion in one of its aspects, that of changing form. But erosion does not always and everywhere present this aspect...

(Fenneman, 1936: 92; cited in: Chorley *et al.*, 1973)

This quote articulates that Davis's theoretical model of landscape evolution did not seek specifically to explain the processes controlling coarse sediment dynamics, but instead simply inferred their role in the progression of fluvial systems through the geographical cycle. This is illustrated in Figure 2.2, where: tectonic activity is responsible for the initial physiography and geology of the fluvial system (youth); climate driven, catchment hydrology then gradually re-shapes the landscape through the operation of geomorphological processes (maturity), until denudation of the catchment as a whole reduces gradients to the point that geomorphological processes become impotent (old age).

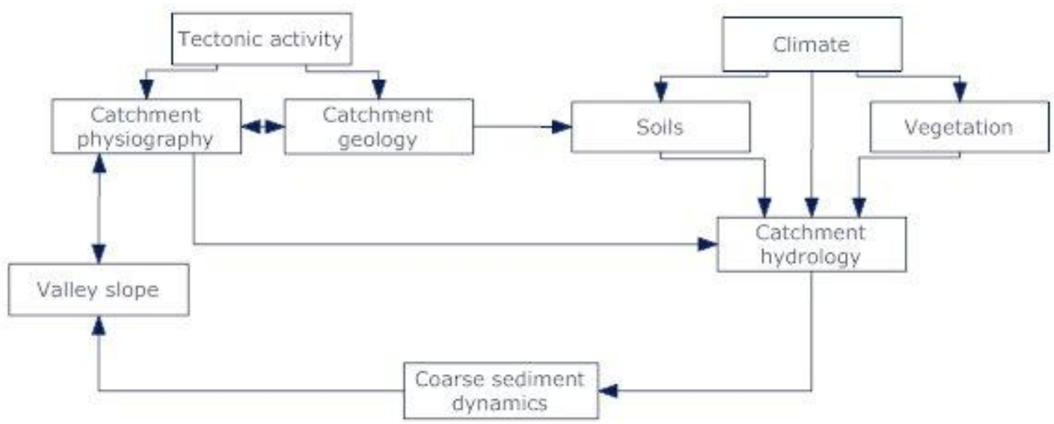

Figure 2.2 Interrelationships in the fluvial system explained by Davis's (1899 cited in Chorley et al., 1973) 'Geographical Cycle'.

However, while this simplified representation of form-process interaction is consistent with Davis's over-arching theories, closer examination of his papers reveals a deeper appreciation for the interaction between coarse sediment dynamics and channel form, especially in his treatment of 'graded' rivers:

...the balance between erosion and deposition...introduces one of the most important problems that is encountered in the discussion of the geographical cycle. The development of this balanced condition is brought about by changes in the capacity of a river to do work, and in the quantity of work that the river has to do. The changes continue until the two quantities, at first unequal, reach equality; and then the river may be said to be graded...

(Davis, 1902: 86-7 cited in Chorley *et al.*, 1973)

It is apparent from this excerpt that Davis did indeed understand the importance of the balance between sediment transport capacity, '*the capacity of a river to do work*', and sediment supply, '*the quantity of work that the river has to do*', in controlling channel morphology and change. Many of the representations of alluvial systems that followed over the next decade reflect these principles. Although Davis clearly understood the significance of coarse sediment dynamics, they are not explicitly represented within his 'geographical cycle', which is concerned with landscape evolution over large temporal and spatial scales.

2.5.3 The functionalist treatment of the transportation of debris by running water

Gilbert's pioneering functionalist work of 1914 provided the quantitative and experimental reference point for many studies of stream debris transport for more than half a century (Clifford, 2008). Straub (1933) described Gilbert's (1914) report as the most outstanding American contribution to observation and measurement of bed load, and the paper may well be the most consistently cited of all sedimentological experiments to date (Clifford, 2008). Gilbert (1914) split the sediment transport phenomenon into three related parts: competence, which led to relations between the size-dependent threshold of debris entrainment and the maximum sediment size in transport; capacity, or the maximum possible weight of load, limited by stream energy, and which was responsive to channel shape and debris calibre and; the relationship between bed forms and the transport of debris.

Gilbert's (1914) experiments yielded three basic equations for stream capacity, written in terms of slope, discharge and 'fineness', and their respective 'competent' (threshold) values for the onset of sediment transport:

$$C = (S - \sigma)^n$$

Equation 2.1

$$C = (Q - \kappa)^o$$

Equation 2.2

$$C = (F - \phi)^p$$

Equation 2.3

where C is transport capacity, S is slope, Q is discharge, F is fineness, σ, κ and ϕ are fixed competence thresholds, and n, o and p are variable exponents. This generated complicated relationships since depth/width ratio and velocity of flow were, in turn, dependent on Gilbert's three driving variables. As a result, Gilbert recognised, although did not necessarily fully comprehend, the presence of complex non-linearity within these relationships stating that:

The rate at which capacity varies inversely with each of the three controlling conditions, slope, discharge, and fineness, itself varies inversely with each of the conditions.

(Gilbert, 1914: 189)

Another important contribution of Gilbert's (1914) paper is its formulation of stream energy and its relationship to sediment transport, although Clifford (2008) identified that both Shaler (1899 cited in Clifford, 2008) and Seddon (1896 cited in Clifford, 2008) had previously recognised the importance of flow energy in controlling the amount of sediment it can transport. Specifically,

The energy of a stream is measured by the product of its discharge (mass per unit time), its slope, and the acceleration of gravity. In a stream without load the energy is expended in flow resistances,…..Load…affects the energy…Its transportation involves mechanical work, and that work is at the expense of the stream's energy…so that the net result is a tax on the stream's energy.

(Gilbert, 1914: 11)

These ideas helped lay the foundations for the rational approach to sediment transport later presented by Bagnold (1966), who identified that the rate of work done in transporting sediment is equal to the available power beyond a threshold value multiplied by efficiency.

Gilbert (1914) also identified a possible quantitative relation between bedform type and the transport stage, and between bedform geometry and the transport rate. His description of bedform regime remains unsurpassed:

When the conditions are such that the bed-load is small,…dunes travel downstream…With any progressive change …tending to increase the load, the dunes eventually disappear and the debris surface becomes smooth. The smooth phase is then succeeded by a second rhythmic phase, in which a system of hills travels upstream. These are called antidunes.

(Gilbert, 1914: 11)

Gilbert's (1914) results showed that changes in bedform regime took place at lower slopes for larger streams and for finer material. This dependence upon particle size and the 'hydraulic size' (the product of velocity and hydraulic radius) was later used to discriminate between lower (dune) and upper (antidune) bedform regimes (Clifford, 2008). Figure 2.3 describes the interrelationships between form and process explained by Gilbert's (1914) studies of sediment transport capacity. It demonstrates how this early functionalist study appreciated that channel slope, discharge, resistance (via velocity and depth/width ratio) and sediment size could all influence sediment transport rate, and that sediment transport rate, in turn, could affect the type of bedforms present in the channel.

Two important aspects of this view of the fluvial system should be appreciated. First, it treats coarse sediment transport as a phenomenon that is independent of time and history, but which must instead be explained by factors that are determinable without reference to the large-scale history or geography of a river catchment. Second, it predominantly treats coarse sediment dynamics in a uni-directional manner: parameters relating to the energy of the flow affect sediment transport rate, which in turn affects the bedform regime without any explicit representation of feedback.

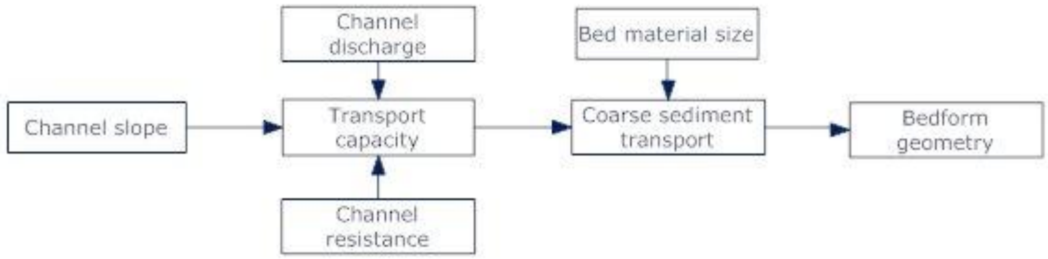

Figure 2.3 Interrelationships in the fluvial system as explained by the functionalist treatment of sediment transport capacity by Gilbert (1914).

However, although focused mainly on sediment transport in simple experimental flumes, Gilbert's (1914) paper also demonstrated an appreciation that his transport relations (Equation 2.1, Equation 2.2 and Equation 2.3) might be limited in their applicability to natural streams. Gilbert (1914) suggested that while the slope and fineness relations might be transferable to natural streams, the discharge relation required modification because the load-discharge relation for natural streams was discontinuous. This discontinuity reflected the 'amplitractional' load: that is, the traction load at a time when the discharge was sufficient to initiate transport from the deeps of a river and 'through transport of bottom load', which included material suspended only by the higher discharges (Clifford, 2008). Further, Gilbert (1914) recognised that, within natural streams, supply limited conditions would render unrealistic predictive sediment transport capacity functions that were developed in experimental flumes with unlimited sediment availability. These recognitions represent an implicit understanding by Gilbert (1914) that coarse sediment dynamics within natural fluvial systems could not be fully represented by simplified, uni-directional, micro-scale treatments of sediment transport capacity alone.

2.5.4 Analytical representation of the alluvial system

Whilst Gilbert's (1914) paper is largely cited with respect to its examination of transport capacity, its central tenet was the development of an analytical framework for describing the alluvial channel system (Clifford, 2008). Gilbert (1914) was dissatisfied with his own attempts to blend laboratory and field experience and concluded that, whilst his ‘laws’ connecting sediment transport capacity individually with its controlling variables had been satisfactorily approached (Equation 2.1, Equation 2.2 and Equation 2.3), his more general proposition linking sediment transport and channel form was, at best, a partial and empirical approximation. Gilbert (1914) was aware that a proper theoretical treatment required consideration of mutual interdependence, and was best expressed by sets of limiting differential equations.

Subsequent studies by Rubey (1938) attempted to couple physically-grounded principles of kinetic energy expenditure to stable ‘graded’ morphological outcomes using Gilbert’s approach. Rubey (1938) developed a theoretical model using the energy consumed in transport:

$$S_e.X^{1/5} = L.v.Q^{6/5}$$

Equation 2.4

where S_e is energy slope, X is the optimum channel form ratio (depth/width), L is transport rate, v is sediment particle settling velocity and Q is discharge. This type of approach proved enlightening with respect to the nature and range of alluvial channel adjustments and its implications were reflected, although not always recognised by, many subsequent research efforts into the relationships between coarse sediment transport and channel form (Clifford, 2008).

The tension between analytical elegance and physical completeness in representations of alluvial channel morphology that typified the analytical approaches of both Rubey and Gilbert was also evident in Lane’s discussion, *‘The Importance of Fluvial Morphology in Hydraulic Engineering’* (1955b). This was a uniquely incisive attempt to draw attention in the engineering community to the geomorphological and geographical character of rivers which ‘structured’ channel form. Lane’s (1955b) analytical model of equilibrium channel form was specified with respect to slope, S, particle diameter, D, and sediment, Q_s (or L), and water discharge, Q_w:

$$Q_s . D \sim Q_w . S$$

Equation 2.5

which has often been reproduced graphically (Figure 2.4). Lane's (1955b) analytical relationship defined the condition of stability between aggradation and degradation of a stream bed and was subsequently interpreted as 'the stable stream balance'. Importantly, it emphasised in-channel aggradation as well as erosion as a form of process-response in the fluvial system. Where the perturbation of a river by, for example, a bend cut-off increases the slope and so disturbs the equilibrium condition of a graded stream, Lane's balance predicts that the channel will respond through degradation, resulting in an increase in bed material load (sediment discharge) and bed material size and a subsequent reduction in slope (Figure 2.4). Explicit recognition of the important role that coarse sediment dynamics (i.e. bed material load) play in the adjustment of channel morphology gives the model a particular strength. This partially explains its widespread acceptance by engineers as a tool for explaining and predicting river response to disturbance. However, though Lane's (1955b) balance represents an admirable early attempt to represent a process-response mechanism that generates feedback between fluvial process and adjustment of channel morphology, it excludes changes in bedforms, channel width, and cross-sectional form, as potential dimensions of adjustment, while planform changes are represented only by the proxy variable of channel slope (Figure 2.5).

It is also interesting to note that, despite Lane emphasising that consideration of W. M. Davis's stages of river development is of *"considerable assistance to hydraulic engineers in their analysis of plans for stream control"* (Lane, 1955b: 11), no explicit representation of long-term channel evolution is included in Lane's analytical representation of stream equilibrium. Instead, like Gilbert's functionalist representation of sediment transport capacity that preceded it, Lane's treatment accounts for coarse sediment dynamics in a manner that is largely disconnected from the evolutionary history of the fluvial system (Figure 2.5).

Surprisingly, despite the potential collaborative benefits, Lane's (1955b) approach was neither referenced back to, nor taken up in, engineering-led, regime analyses, which had been steadily increasing in sophistication during the same period (Clifford, 2008), as will be examined in the next section.

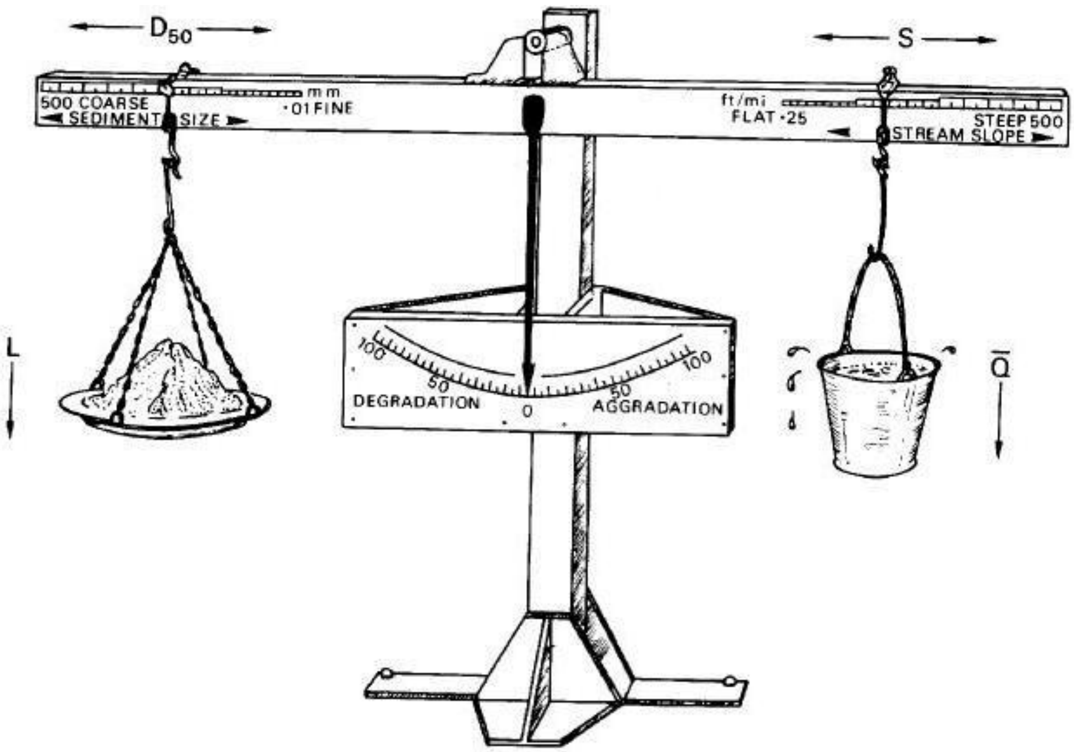

Figure 2.4 Graphical illustration of Lane's (1955b) analytical treatment of coarse sediment dynamics within the alluvial system. Diagram originated as an unpublished drawing by W. Borland of the US Bureau of Reclamation.

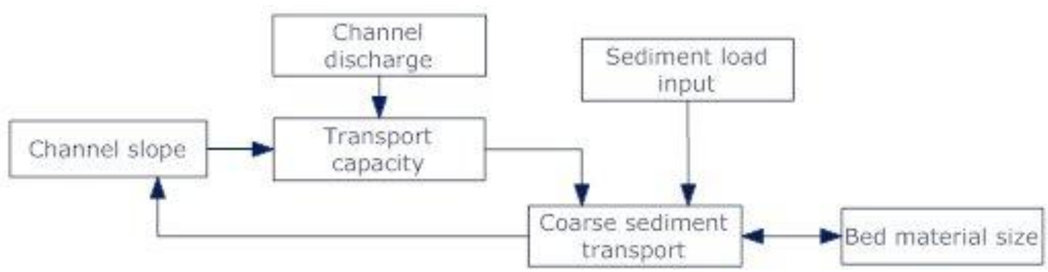

Figure 2.5 Interrelationships in the fluvial system as explained by the analytical representation of coarse sediment dynamics by Lane (1955b).

2.5.5 Regime theory

As identified in Section 2.1, the large-scale and highly bureaucratised civil water works in India created a huge natural data-producing laboratory that acted as the foundation for 'regime theory' that was developed by British engineers. Three situations requiring engineering design solutions were commonly encountered: using the lowest practicable velocity to minimise slope in order to increase the irrigation command area; reducing the dimensions of a canal to limit land take and/or cost, which involved maximising velocity while maintaining bed and bank stability; and making slope as steep as possible to reduce the cost of a step in the long profile or avoid alignment difficulties. These practical problems led to scientific consideration for the implications that channel slope, channel shape, channel boundary material and the characteristics of transported load had for the stability of canals (Lacey, 1939).

The regime theory that developed from these scientific studies was a set of quantitative, and essentially empirical 'laws' of channel self-formation. The regime canals carried seasonally heavy loads of relatively fine sediments, but for most of the year, were maintained in a state of constant discharge (Clifford, 2008). Regime theory dictated that a degree of variation in channel shape was inevitable but that, in general, transient in-stream bars would only vary local slope and width about a more consistent longer-term state. The rationale was that:

> *..river variables are not as erratic as commonly supposed...regime behaviour consists of a fluctuation about an equilibrium position, or about a trend to an equilibrium position that, presumably, must depend on some laws of self-adjustment capable of quantitative expression.*
>
> (Blench, 1957: 11)

Kennedy (1895 cited in Clifford, 2008) published pioneering relations between depth and discharge for 22 canals in the Lower Bari Doab Canal System, which he considered as stable examples from a larger sample. He was concerned with empirically identifying the conditions of 'full supply' in which channels neither silted nor scoured their beds. Based on his sample of stable canals, he identified that, once a channel had ‘settled’ itself, the mean speed of flow was a function of depth of the form:

$$V_0 = C.d^n$$

Equation 2.6

where V_0 is the critical mean velocity, d is depth, C is a calibration value (which varies with the quantity and calibre of silt) and n is a constant (0.64). Three new irrigation systems were designed using Kennedy’s empirical formula, but these experienced varying degrees of problems over several decades (Clifford, 2008).

Later advances in regime theory included recognition that slope and width (Garrett, 1909 cited in Clifford, 2008), and also bed material, bank material and discharge (Lindley, 1919 cited in Clifford, 2008) were significant aspects of self-adjustment within canals. However, it is the work of Lacey, published after 1930, which is the most widely cited contribution to regime theory. Lacey justified the empirical nature of regime theory by arguing that physical laws must underpin widely-observed regularities. His approach was to determine ‘true’ values, that lay within the limits of an assumed statistical relationship, from empirical scatter attributed to observational error and circumstance (Clifford, 2008). As such, Lacey’s work presaged the research of Leopold and others in the 1950s and 1960s. His efforts (Lacey, 1933-1934; Lacey, 1939) produced the following equations:

$$P = 2.668 \cdot Q^{0.5}$$

Equation 2.7

$$V = 0.07937 \cdot Q^{1/6} \cdot f^{1/3}$$

Equation 2.8

$$\frac{P}{R} = 5.65 \cdot Q^{1/6} \cdot f^{1/3}$$

Equation 2.9

$$S = \frac{f^{5/3}}{1788 \cdot Q^{1/6}}$$

Equation 2.10

where P is the wetted perimeter, Q is the discharge, V is the velocity, f is the silt factor related to the diameter of the bed material, D (in inches), by $f = 8 \cdot D$, R is the hydraulic radius and S is the slope.

Using Lacey's regime equations, if both the silt factor (f) and the discharge (Q) were known, the stable wetted perimeter, hydraulic radius and slope of a canal were uniquely determinable so that stable geometries could be seen as direct outcomes of the interaction of determinate processes. Later research efforts by Inglis (1949) and Blench (1957) added channel planform to the aspects of channel morphology that could be predicted using the regime approach.

It is evident that the regime theory approach developed and practised by Kennedy, Lacey, Inglis, Blench and others was not concerned with geomorphological processes occurring over large temporal and spatial scales but, like the approaches of Gilbert (1914) and Lane (1955b), treated the systems as time and space independent. As the channels in question were artificially constructed, with steady flows and uniform dimensions, the systems were largely space and time independent. Further, the regime theory they developed did not explicitly attempt to explain the processes responsible for coarse sediment dynamics. Instead, it simply described the relationships between those parameters deemed as being independent (discharge and boundary material size) and those deemed as being dependent (channel morphology). In other words, whilst Lacey recognised that physical laws must underpin the 'widely-observed regularities' in regime canals, he did not attempt to explain those laws. Instead he sought to define the trends that the 'black-box' of coarse sediment dynamics generated. This is reflected in Figure 2.6.

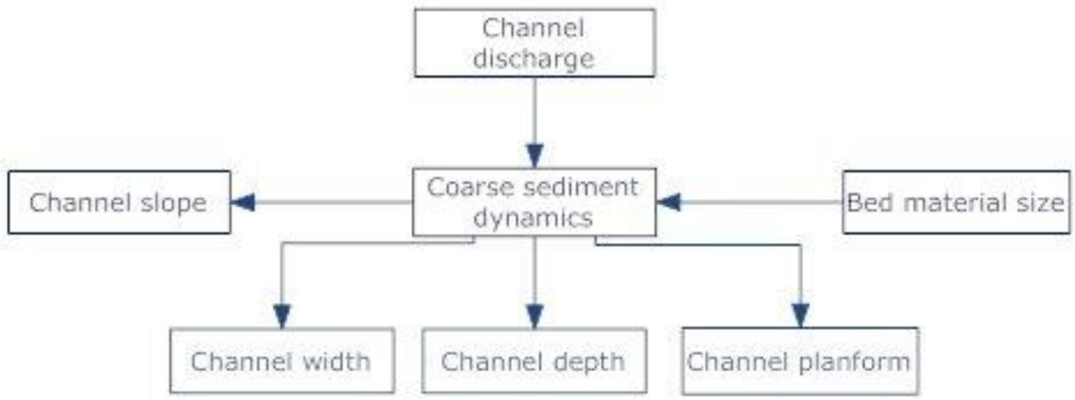

Figure 2.6 Interrelationships in the fluvial system as explained by regime theory.

2.5.6 Critical tractive force and the design of stable channels

In 1948, the Bureau of Reclamation of the US Department of the Interior began a series of reviews and experiments with the aim of improving the design of irrigation canals constructed in earth. These efforts were formalised into a design method by Lane (1955a). Whereas the European regime approaches accommodated a limited degree of morphological adjustment reflecting the joint controls of discharge and load, this approach was based upon:

…securing a distribution of the tractive force along the sides and bottom of the channels such that the magnitude of this force at all points will be sufficiently large to prevent sediment deposits in objectionable quantities, and at the same time will be small enough to prevent objectionable scour.

(Lane, 1955a: 1234)

The identification of a means to design stable channels, where no erosion or deposition occurs, proceeded in three stages (Clifford, 2008):

i. clarification of the general principles for stable canal design;
ii. development of a tentative method to assure freedom from scour, whereby critical tractive force was determined from the velocity distribution and particle size in channels of trapezoidal cross section; and
iii. the formulation of specific criteria for the design of canal shapes which involved a minimum of excavation, in coarse non-cohesive material.

There are clear similarities between the European regime approach and the US approach to stable channel design based on the concept of critical tractive force. Similarities include not only comparable applications, but also the treatment of geomorphological processes over similar scales. However, attempts to make direct linkages by Simons and Albertson (1960) and Henderson (1963) were met with general hostility, largely due to disagreements over the acceptability of active sediment transport. These disagreements highlight an important difference between the two approaches: the American critical tractive force approach to stable channel design was not a purely empirical but incorporated a theoretical analysis of the balance of motivating and resisting forces acting on the coarse material composing the channel boundary. However, the critical tractive force approach explicitly sought to design stable, threshold channels in which the motivating forces never exceeded those resisting entrainment. Hence, while this approach sought to account for the process of coarse sediment entrainment, it made no attempt to predict how channel morphology might adjust in 'unstable' channels where sediment transport, erosion or deposition did occur (Figure 2.7).

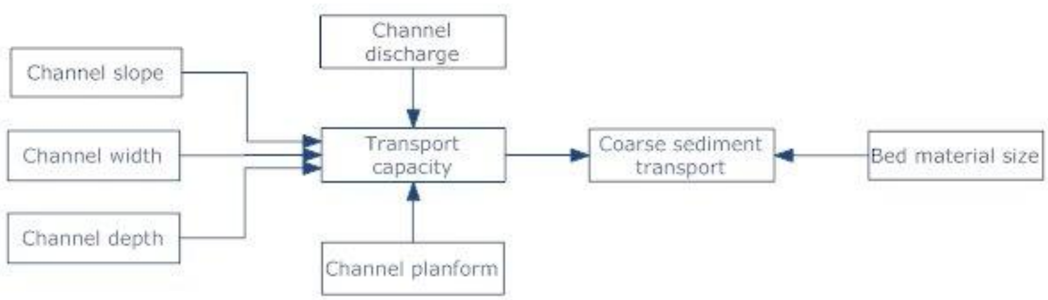

Figure 2.7 Interrelationships in the fluvial system as explained by the tractive force approach to stable channel design.

2.5.7 Hydraulic Geometry

'The Hydraulic Geometry of Stream Channels and Some Physiographic Implications' (Leopold and Maddock, 1953) aimed to take "*Quantitative measurement of some of the hydraulic factors that help determine the shape of natural stream channels*" and *"...provide some picture of the hydraulic characteristics related to channel shape and a segment of the stream's sediment*

load…to be potentially useful tools for the study of fluvial processes” (Leopold and Maddock, 1953: 2). The justification for their approach was that:

The channel characteristics of natural rivers are seen to constitute, then, an interdependent system which can be described by a series of graphs having simple geometric form. The geometric form of the graphs describing these interactions suggests the term ‘hydraulic geometry’. Channel characteristics of a particular river system can be described in terms of the slopes and intercepts of the lines in the geometric patterns

(Leopold and Maddock, 1953: 18)

In their paper, Leopold and Maddock (1953) fit power law relations to graphs of width, depth, velocity and suspended sediment load as functions of discharge for reaches of 20 American rivers. Data were derived from USGS gauging station records for streams in the Great Plains and the southwest. The mean annual discharge and cross-sectionally averaged velocity were used for convenience and due to limited data availability.

Leopold and Maddock (1953) identified changes both along rivers ‘downstream hydraulic geometry’, and changes at individual cross-sections, ‘at-a-station hydraulic geometry’. They defined downstream hydraulic geometry of a catchment (or collection of catchments) using a constant flow frequency, so that the channel dimensions change as the discharge relating to that flow frequency increases in a downstream direction due to increasing drainage area and tributary inputs. At-a-station hydraulic geometry describes how width, depth, velocity and load increase at a given cross-section as discharge increases. The functions for both types of hydraulic geometry differ only in terms of the values of coefficients and exponents and, based on the regression curves fitted to the field data, Leopold and Maddock (1953) defined hydraulic geometry using the following ‘power laws’:

$$w = aQ_{MAF}{}^{b}$$

Equation 2.11

$$\bar{d} = cQ_{MAF}{}^{f}$$

Equation 2.12

$$\bar{u} = kQ_{MAF}{}^{m}$$

Equation 2.13

$$\mathrm{L} = pQ_{MAF}{}^{j}$$

Equation 2.14

where w is width; $\bar{d}$ is mean depth; $\bar{u}$ is mean velocity; L is suspended sediment load; and Q_{MAF} is the mean annual discharge, and b = 0.26, f = 0.40 and m = 0.34 for at-a-station hydraulic geometry. The exponents for downstream hydraulic geometry were 0.5, 0.4 and 0.1 (Leopold and Maddock, 1953).

Because of the alternatives offered to engineers by regime theory and critical tractive force approaches, uptake of hydraulic geometry equations for use in stable channel design was relatively weak (Clifford, 2008). This was unfortunate in that downstream hydraulic geometry represents a less restrictive extension to regime theory, a fact that Blench (1957) recognised, stating:

The USGS work [by Leopold and Maddock] *might be described as a regime analysis of fairly trapezoidal sections in river systems, exactly parallel to the Lacey regime analysis..of canal systems, although its authors had an original outlook unbiased by any theory.*

(Blench, 1957: 99)

Regime theory and hydraulic geometry attempted to 'explain' the influence that coarse sediment dynamics has on channel morphology in a similar manner. Both explanations of form-process interaction was rendered in two stages (Clifford, 2008). First, they assumed that the existence of physically-determinate behaviour could be inferred from statistical trends, with departures from the trend attributed to errors and a variety of uncontrolled variables. Second, they inferred physical mechanisms from correlations between proxy variables, sometimes without detailed theoretical consideration of the causal relations responsible for those correlations. As a result, like regime theory, hydraulic geometry's treatment of coarse sediment dynamics can be considered to be a 'black-box' approach, with a representative, 'dominant' discharge being the explanatory variable for cross-sectional geometry, velocity, slope, planform pattern and channel resistance *via* the inferred physical processes related to coarse sediment dynamics (Figure 2.8).

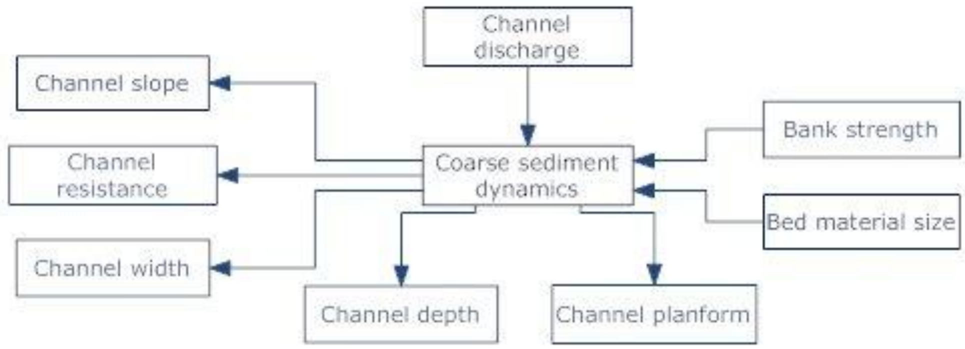

Figure 2.8 Interrelationships in the fluvial system as explained by hydraulic geometry.

However, whilst recognising the similarities between hydraulic geometry and regime theory, Clifford (2008) argued that they differ in several respects. Importantly, regime theory was concerned less with 'explanation' and more with correlation and comparison, so that the statistical best fit between flow and form was of more significance than explanation of the processes linking them. This was evident from the fact that both the coefficients and exponents used within regime theory were subject to alteration. Clifford (2008) highlights that the consequences of this contrast in approach are clearly seen in the contrasting manner with which regime theory and hydraulic geometry treated ideas of a reference discharge, and which led Inglis to condemn hydraulic geometry based upon mean annual discharge as *'..quite valueless for correlation purposes'* (1961: 214).

Nevertheless, hydraulic geometry remains similar to regime theory in its attempt to find general trends in fluvial form. This focus on overall trends was justified by Leopold and Langbein since...

Any aspects of science may founder temporarily on the shoals of small questions of details, as well as on the dead-end shallows of description. Resurgence of activity and interest can revitalize a subject where the questions posed for investigation are big ones,...which..have wide applicability or lead to broad generalization.

(Leopold and Langbein, 1963: 192)

While the general trends identified by hydraulic geometry analyses were not initially taken up by the engineering-based, stable channel design community, they were widely applied by geomorphologists intent on the identification of equilibrium conditions and quantification of the graded river profile (Clifford, 2008). However, in many of the early applications, attempts to identify equilibrium conditions based on hydraulic geometry analysis were disappointing. Ultimately, in its reliance on the 'channel forming discharge' as a proxy for channel processes and their interactions, hydraulic geometry proved to be a very blunt diagnostic tool (Clifford, 2008). In fact, reconciling a morphologically defined flow, like bankfull discharge, with an event of specified flow frequency, such as the 2-year return period flow, remains an unresolved issue at the heart of the downstream hydraulic geometry approach (Soar, 2000).

Nevertheless, the hydraulic geometry of stream channels was a paradigmatic starting point for much future work. Along with Horton's paper on streams and drainage basins (1945), it established both the means and the rationale for a working relationship among geomorphologists, hydrologists and engineers. In this very success, however, it may have overshadowed the longer-standing tradition of more robust, process-driven studies, present in both the geographical and geological traditions of geomorphology (Clifford, 2008). These did not strongly re-emerge until the late-1970s, despite the work of Schumm (see below). Mackin (1963) highlighted this notable concern in his critical comment on the new, but essentially empirical, methods of analysis that had been drawn into geology from the physical sciences and engineering.

2.5.8 Schumm's Fluvial System

Stanley A. Schumm was primarily a leading figure within hydraulic geometry and functionalist geomorphology as a whole. He produced several papers that attempted to quantify fluvial forms and processes that were implicitly based on the dominance of extant physical processes over channel form (e.g.: Schumm, 1960; Schumm, 1963; Schumm, 1968; Schumm, 1969; Schumm, 1971; Schumm and Khan, 1972). Probably the most influential of his functionalist works was his attempt to predict the direction of response that channels will go through following a disturbance (Schumm, 1969). As with his contributions to hydraulic geometry, this study was based upon empirical relationships using data from sand-bed channels in semi-arid and sub-humid regions of the United States and Southeastern Australia. Using a series of empirically-based hydraulic geometry equations relating channel variables to flow and sediment characteristics Schumm (1969) generated a series of rules that predicted changes in morphological condition in response to changes in discharge and bed-load supply. Discharge (Q) and bed-load supply (Q_b) can increase ($+$), decrease ($-$) or remain unchanged. The predicted changes in width (w), depth (d), width/depth ratio ($^{w}/_{d}$), meander wavelength (λ), channel slope (s) and sinuosity (S) were indicated as being either an increase ($+$), a decrease ($-$), or indeterminate ($\pm$). Schumm's (1969) predictive relationships resulting from changes in either discharge or supplied bed-load were:

$$Q^{+} \longrightarrow w^{+} \quad d^{+} \quad \left({}^{w}/_{d}\right)^{+} \quad \lambda^{+} \quad s^{-}$$

Equation 2.15

$$Q^{-} \longrightarrow w^{-} \quad d^{-} \quad \left({}^{w}/_{d}\right)^{-} \quad \lambda^{-} \quad s^{+}$$

Equation 2.16

$$Q_b{}^{+} \longrightarrow w^{+} \quad d^{-} \quad \left({}^{w}/_{d}\right)^{+} \quad \lambda^{+} \quad s^{+} \quad S^{-}$$

Equation 2.17

$$Q_b{}^{-} \longrightarrow w^{-} \quad d^{+} \quad \left({}^{w}/_{d}\right)^{-} \quad \lambda^{-} \quad s^{-} \quad S^{+}$$

Equation 2.18

However, Schumm (1969) recognised that changes in discharge and sediment load rarely occur independently from each other because of their joint dependence on watershed characteristics, but he discovered that attempting to account simultaneously for changes in both resulted in increased indeterminacy within his predictive relationships:

$$Q^{+} \quad {Q_b}^{+} \longrightarrow w^{+} \quad d^{\pm} \quad \left({}^{w}/_{d}\right)^{+} \quad \lambda^{+} \quad s^{\pm} \quad S^{-}$$

Equation 2.19

$$Q^{-} \quad {Q_b}^{-} \longrightarrow w^{-} \quad d^{\pm} \quad \left({}^{w}/_{d}\right)^{-} \quad \lambda^{-} \quad s^{\pm} \quad S^{+}$$

Equation 2.20

$$Q^{+} \quad {Q_b}^{-} \longrightarrow w^{\pm} \quad d^{+} \quad \left({}^{w}/_{d}\right)^{\pm} \quad \lambda^{\pm} \quad s^{-} \quad S^{+}$$

Equation 2.21

$$Q^{-} \quad {Q_b}^{+} \longrightarrow w^{\pm} \quad d^{-} \quad \left({}^{w}/_{d}\right)^{\pm} \quad \lambda^{\pm} \quad s^{+} \quad S^{-}$$

Equation 2.22

Schumm's (1969) approach bears a striking similarity to Lane's (1955b) analytical representation of coarse sediment dynamics, reviewed in Section 2.5.4. Both approaches are informed by an understanding of the physical processes involved in coarse sediment dynamics though they are based on rules developed empirically. Additionally, both approaches produce predictions of characteristic types of channel response that indicate the likely direction of change, but give no indication of the extent of change or the rate at which it will occur. However, like Lane's (1955b) approach, Schumm's rules have been widely and successfully employed in applied fluvial geomorphology, particularly in assessing the effects of human disturbance of the fluvial system (Knighton, 1998). However, predictions using this type of approach are limited when based purely upon empirical relationships without due consideration for the physical processes involved. For example, dams generally decrease both the discharge and sediment load supplied to downstream reaches so that Equation 2.20 ought to apply. However, in a study of 17 dams in the USA, Williams and Wolman (1984) found that 46% of sections widened, 26% narrowed, and 22% retained a constant width.

Despite the significance of his contributions to fluvial geomorphology from a functionalist perspective, arguably Schumm's most significant achievement was his recognition, and successful communication, of the fact that, whilst the fluvial system can be regarded as either a physical system (eg: Gilbert, 1914; Lacey, 1939; Leopold and Maddock, 1953; Lane, 1955b) or a historical system (e.g. Davis, 1899 cited in Chorley *et al.*, 1973), in reality it is a physical system with a history (Schumm, 1977). He argued that present form is influenced by both past and present conditions, where 'present' is defined as the time period over which inputs to the fluvial system have remained relatively constant. These arguments echoed those of Simpson (1963), who reasoned that geomorphological studies must distinguish between 'immanent', ahistorical processes that may always occur (under the appropriate historical circumstances), and 'configurational', states which are the result of the interaction of the immanent with historical circumstances. Until that point there had been an uncomfortable tension between the functionalist approach to geomorphology, which related extant forms to extant processes and centred around Gilbert's (1877) concept of natural systems being in dynamic equilibrium; and the evolutionary or historical approach to geomorphology, which focused on Davis's (1899 cited in Chorley *et al.*, 1973) concept of progressive changes in the landscape through time. Chorley (1962: 3) recognised the difficulty in reconciling the long-term cycle of erosion and short-term dynamic equilibrium as, *"in the former...the useful concept of dynamics equilibrium or grade rests most uncomfortably; in the latter...the progressive loss of a component of potential energy due to relief reduction imposes an unwelcome historical parameter"*.

Through publication of *'Time, space and causality in geomorphology'* Schumm and Lichty (1965) had a major impact upon the way in which geomorphologists view Earth systems. They argued that *'distinctions between cause and effect in the moulding of landforms depend on the span of time involved and on the size of geomorphic system under consideration'* (Schumm and Lichty, 1965: 110). Their paper describes how different cause-effect relationships become of primary importance as the dimensions of time and space change. This was a criticism of the functionalist geomorphologists of the day, who were solely concerned with *"applying themselves to modern problems"* which curtailed the *"spatio-temporal range of their research"* and neglected the important historical aspect of landscape evolution (Schumm and Lichty, 1965: 111). Instead Schumm and Lichty (1965) argued that geomorphologists should and could account for both: ‘historic’ landscape development, over a ‘cyclic’ time-scale where local-scale variables are of little relevance; and ‘present’ physical processes, over a ‘graded’ time-scale where catchment-scale variables are held relatively constant. Similarly, Simpson (1963: 29) argued that because events *“...are determined by the immanent characteristics of the universe acting on and within particular configurations...”* every event is unique.

Within a fluvial system, the characteristics of the system change over the long span of cyclic time due to the semi-continual removal of material and expenditure of potential energy (Figure 2.9A). When a fluvial system is viewed from this perspective: time, geology, initial relief, and climate are the independent variables driving the system; long-term hydrology, relief and valley dimensions are the dependent variables of interest; and the forms and processes occurring at the channel-scale are irrelevant (Schumm and Lichty, 1965). Conversely, over a graded sub-set of cyclic time, dynamic equilibrium exists in those locations where the landforms have reached a graded condition in relation to the processes acting on them (Figure 2.9B). Within this time-span, the graded condition can apply only to individual components of the drainage basin – while the entire system cannot be graded, an individual reach may be. When a fluvial system is viewed from this perspective: time, and the initial relief of the system are irrelevant; instead the reach is controlled by its contemporary hydrology and sediment input (i.e. the flow and sediment regimes), along with the local valley terrain and dimensions. Reach-scale hydraulics, sediment transport processes and the channel morphology with which they interact are the dependent variables of interest at this time-scale (Schumm and Lichty, 1965).

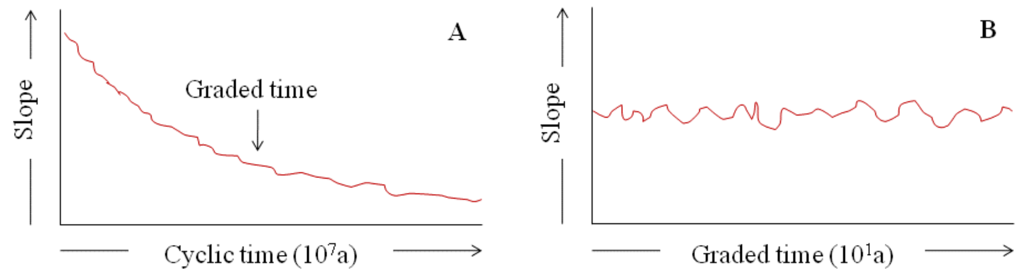

Figure 2.9 Alternative time-scales over which river channel morphology can adjust. Channel gradient has been arbitrarily selected as the variable of interest. (A) Progressive reduction of channel gradient during cyclic time. (B) Fluctuations above and below a mean during graded time. Modified from Schumm and Lichty (1965).

As well as formally addressing the importance of perspective in terms of temporal and spatial scales, Schumm made another significant contribution to the treatment of time and space with respect to the study of coarse sediment dynamics through his identification of threshold behaviour and complex response in the fluvial system (Schumm, 1973; Schumm, 1977). Characterisation of geomorphology as a system science had actually been proposed earlier by Chorley (1962; 1971), but Schumm (1973) is widely cited as developing many of the most important conceptual and practical applications of the system framework.

Exploring coarse sediment dynamics within a systems approach overcame the practical limitations of reductionist science – it opened the way to modelling complex patterns of interaction between the various subsystems that make up the fluvial landscape. It replaced analytical theories with system models as generalisations of the landscape in a manner that can conceivably be more faithful to the prototype (Church, 2010). Since the alluvial and morphological details of drainage systems are much too complex to be explained by progressive erosion alone, Schumm (1973) identified that they are affected by abrupt modifications as a result of both *geomorphic thresholds* and *complex response*.

'Geomorphic thresholds' separate different system regimes, each of which may have its own characteristic morphology. Schumm (1973) recognised two types of threshold: extrinsic, which are associated with a change in an external factor such as climate; and intrinsic, which reflect an inherent property of geomorphic systems to evolve to a critical state when adjustment or failure occurs.

As a result of fluvial systems crossing these thresholds, Schumm (1975) suggested that, rather than remaining in a state of dynamic equilibrium, where they continually adjusted to maintain equilibrium with their environment, fluvial systems commonly existed in a 'dynamic, metastable equilibrium', where occasional, abrupt changes punctuate dynamic stability in the fluvial system.

Schumm (1973) also argued that, because of the large number of interrelationships in the fluvial system, its response to disturbance is often complex. His key example was the response of a drainage system to rejuvenation by a change in base level, which was simulated in the Rainfall Erosion Facility (REF) at Colorado State University (CSU):

> *...a small drainage system...was rejuvenated by a slight (10 cm) change of base level. As anticipated, base level lowering caused incision of the main channel and development of a terrace... Incision occurred first at the mouth of the system, and then progressively upstream, successively rejuvenating tributaries and scouring the alluvium previously deposited in the valley... As erosion progressed upstream, the main channel became a conveyor of upstream sediment in increasing quantities, and the inevitable result was that aggradation occurred in the newly cut channel... However, as the tributaries eventually became adjusted to the new base levels, sediment loads decreased, and a new phase of channel erosion occurred...*
>
> (Schumm, 1973: 307)

Ashworth and Ferguson (1986) also recognised the complex interactions that occurred between coarse sediment transport and channel morphology. They described cause-effect relationships in active gravel-bed rivers as being closely interlinked with substantial feed-back, both positive and negative, as indicated by Figure 2.10. This figure was derived on the basis of experimental work on a proglacial braided river where they found that channel morphology, itself produced by the interaction of previously imposed discharge and sediment supply, determines the way in which current sediment supply and discharge fluctuations interact to cause particular patterns of morphological change. In other words, a strong coupling between form and process is manifest as a spatially distributed form-process feedback and exhibits complex response in fluvial systems.

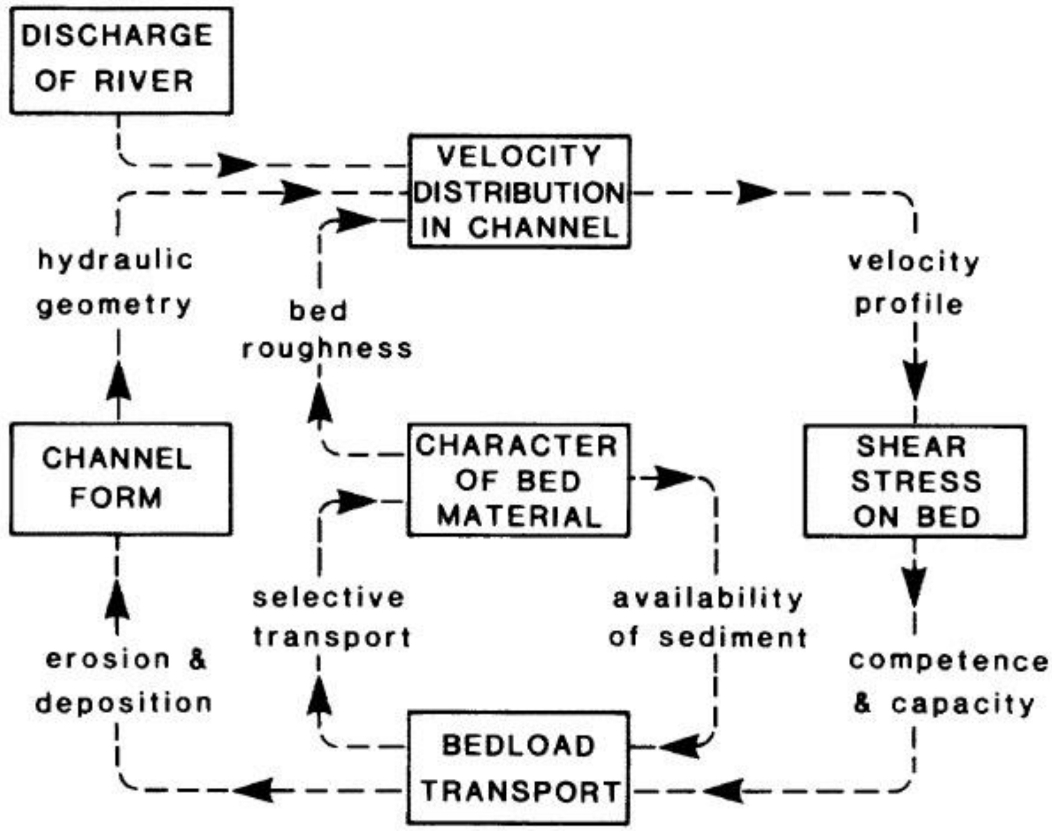

Figure 2.10 Interrelationships amongst form flow and sediments in active gravel-bed rivers. Taken from Ashworth and Ferguson (1986).

Through application of the concepts of threshold behaviour and potential complex response, Schumm (1973) demonstrated that, within a natural system, a single disturbance can trigger a complex reaction as the components of the system respond progressively to perturbation in what has since been termed 'spatially distributed form-process feedbacks' (Lane and Richards, 1997). These principles provided an explanation of the complexities observed in alluvial chronologies, and suggest that an infrequent event, although performing little of the total work within a drainage system, may, in fact, be the trigger that causes the crossing of a geomorphic threshold and the catalyst for a complex sequence of events that will produce significant landscape modification. These ideas recognise the importance of connectivity in the fluvial landscape, both over time and space, in a manner that had not been explained by previous approaches to understanding coarse sediment dynamics, such as hydraulic geometry and regime theory. Schumm's original contribution, along with those of his peers and students, allowed fluvial geomorphologists to view coarse sediment dynamics from a fresh perspective, as illustrated in Figure 2.11.

Although functionalist approaches to studying fluvial forms and processes continued to dominate thinking throughout the period during which Schumm's new ideas of the fluvial system were being published, the last decades of the 20th century saw researchers identifying that the fluvial system did indeed have a 'memory'. For example, Warner (1987; 1994) identified that the oscillation between flood- and drought-dominated flow regimes in the coastal rivers of New South Wales gave rise to a cyclic disequilibrium in channel form, from a condition that was nearing equilibrium for 'historical' drivers into a condition in equilibrium with 'present' drivers, before the changing flow regime created new 'future' drivers. Over far longer time-scales, the channel patterns and deposits of Amazon Basin rivers draining Andean source areas have been shown to reflect the effect of Pleistocene glacial episodes when the uplands supplied large quantities of coarse bed-load, which only the major rivers are now able to rework (Baker, 1978). Similarly, Church and Slaymaker (1989) suggest that fluvial adjustment to post-glacial conditions is incomplete in British Columbian rivers because of the constraints imposed by relict boundary sediments.

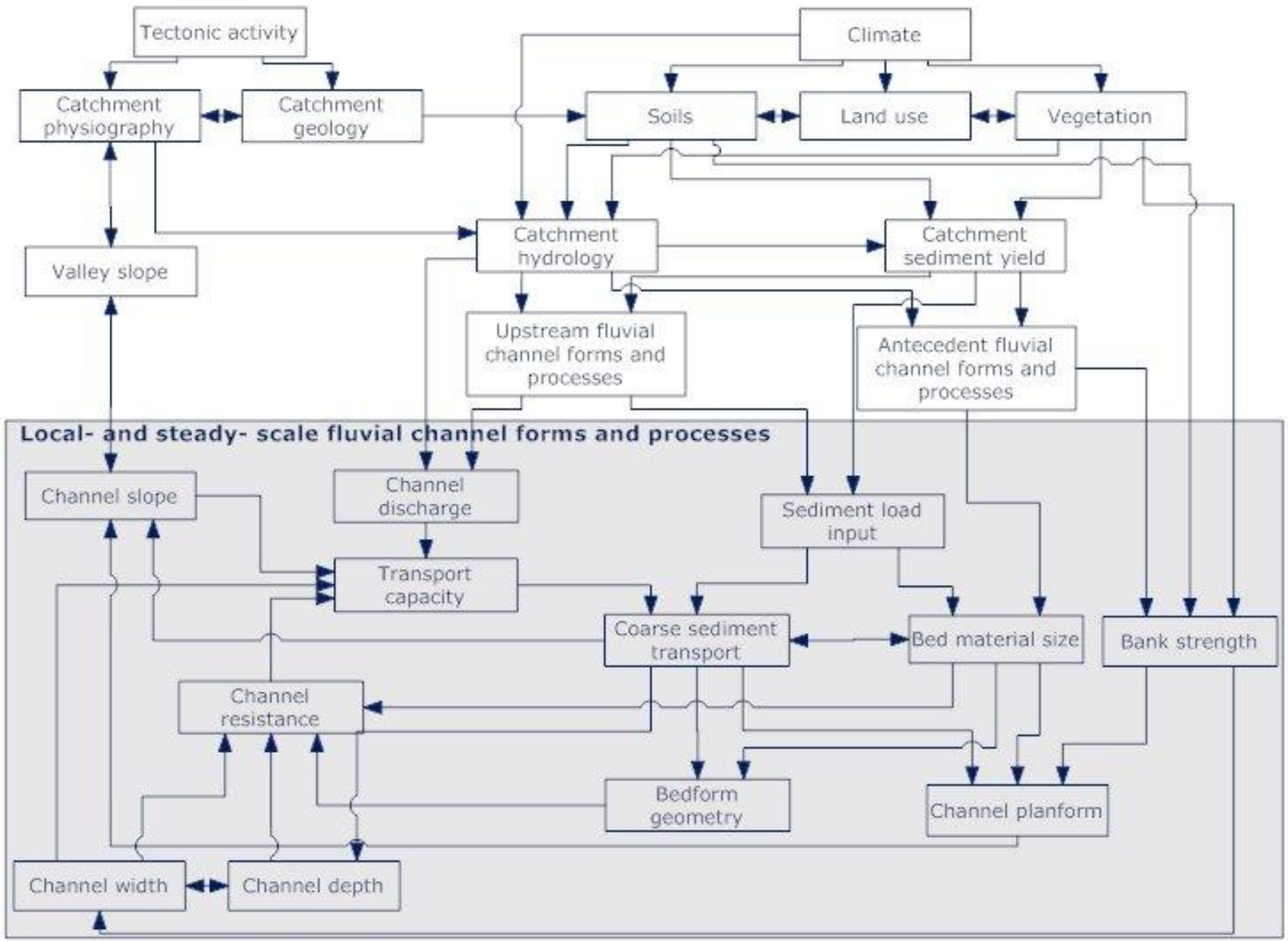

Figure 2.11 Interrelationships in the fluvial system as explained by Schumm's alluvial system.

2.5.9 Non-linear dynamics

Schumm's (1965) separation of modes of examining geomorphological processes based on the temporal and spatial scales under consideration has received some important criticism. Notably, Lane and Richards (1997: 257) suggested that the idea that different scales of form and process are causally independent of each other is unsustainable *"as short time-scale and small space-scale processes influence processes over longer time-scales and larger space-scales".* Based on observations within a braided reach of an actively changing river in the Swiss Alps, they argued that, since the changes in morphology resulting from small-scale channel processes can impact future channel processes in a non-linear fashion, local characteristics are important in controlling future system behaviour.

Non-linear behaviour is defined to occur when the outputs of a system are disproportional to the inputs over the entire range of inputs (Phillips, 2003). A highly non-linear relationship exists between fluxes of water and coarse sediment in river systems (Cudden and Hoey, 2003), and this is significant in generating non-linear behaviour in many aspects of fluvial systems including hydraulic geometry relationships, hysteresis effects, meander migration rates, the probability of an avulsion, relations between flood magnitude and sediment load, the existence of bed-load pulses, and the response of drainage basins to catchment changes in climate and land-use (Coulthard and Van de Wiel, 2007). Non-linear behaviour has three serious implications for coarse sediment dynamics:

i. the fluvial system may exhibit sensitivity to the initial conditions, as changes in the inputs to the system can instigate disproportionate changes in its outputs;
ii. the behaviour of a system may exhibit either divergent or convergent emergent properties, which cannot be expressed as a sum of the behaviours of its components;
iii. because the emergent behaviour of a non-linear system cannot be inferred from its components, a future state of the system can often only be known

by direct observation at that future time — either in nature or in a model of the system.

Figure 2.11, which is based upon Schumm's fluvial system, also adequately describes how its non-linear behaviour explains the impact that coarse sediment dynamics has on channel morphology. The key advance lies in recognition of how high levels of complexity can arise from non-linear relationships and feedback loops that are inherent to the fluvial system (Phillips, 2003).

2.5.10 Computational models

Since the 1980s there have been major advances in computer-based simulation models of fluvial processes. Such models provide a valuable tool for interpreting and understanding the complexities of change within fluvial systems. Indeed, whilst the characterisation of geomorphology as a system science had been introduced in the 1960s and 1970s (Chorley, 1962; Chorley and Kennedy, 1971), quantitative application and development of the concept could really only begin following the advent of digital computers capable of modelling geomorphological systems numerically (Church, 2010). A variety of different types of models has been developed, each simulating coarse sediment dynamics at a particular scale.

At one end of the scale are high-resolution, Computational Fluid Dynamics (CFD) models. These are based on representing the fundamental physics of flow, giving them intensive computational requirements, and consequently the simulations they can support generally represent short periods of time, such as a single flood event, and small spatial extents, such as a channel reach, or sub-reach. CFD models have been used in many different applications including meander formation (Olsen, 2003).

Coarse sediment dynamics can also be quantified using sediment modules available within established, 1-D hydraulic models such as HEC-RAS 4.0 (Brunner, 2006) and ISIS (ISIS, 1999). These models work by solving the St. Venent equations for gradually varied, unsteady flow to predict flow velocities and depths, and then using a coupled sediment transport function to calculate a sediment transport rate, based on a user-specified flood hydrograph, and a series of channel/floodplain cross-sections.

A potentially significant, relatively recent development has been the application of cellular models to represent fluvial systems in a less physically complete, but consequently less computationally demanding, manner. The transfer of water and sediment between cells is simulated using simple rules, which are based on the underlying physics that govern those processes (Nicholas, 2005). Because of their reduced computational demands they can be applied over large temporal and spatial scales and have been used to provide representations of braided rivers (Murray and Paola, 1994), alluvial fans (Coulthard, 2002) and even entire river catchments (Coulthard *et al.*, 2005).

Reach-based sediment balance models have also been used to provide simplified representations of coarse sediment dynamics across entire river catchments (Biedenharn *et al.*, 2006b). They divide the fluvial network into a series of contiguous discrete reaches, averaging morphological properties within each reach. Based on these averaged morphological properties, they predict the coarse sediment transport capacity of each reach and compare adjacent reaches to make judgements about whether each reach has the tendency to accumulate or export sediment in an average hydrometric year.

Any model of coarse sediment dynamics represents a simplified abstraction of the complex natural system that is being modelled. Models simplify reality, with only those components that are perceived to be of interest being represented in a given model. In other words, a computer simulation model should be regarded as a useful aid to understanding, but should not be seen as a substitute for direct observation (Wainwright and Mulligan, 2004).

2.5.11 Synthesis

Based on the above review, it is apparent that scientific approaches to the treatment of coarse sediment dynamics within river channels and fluvial systems have varied dramatically over the past 120 years. Early treatment of the fluvial system by Davis's (1899 cited in Chorley *et al.*, 1973) 'geographical cycle' did not explicitly explain the means by which coarse sediment transport influenced channel morphology, instead focussing on description of the impacts that the erosion and transfer of coarse sediment over cyclic time-scales had over landscape-scale physiography. Davis's broad-scale, evolutionary approach was superseded by the functionalist approach to explaining coarse sediment dynamics, initially led by Gilbert (1914), and later modified by, amongst others, Lacey (1939), Lane (1955b), and Leopold and Maddock (1953). Although the nature of the functionalist approaches these researchers developed differed, they were similar in that they focused on describing and/or explaining local-scale coarse sediment dynamics over a graded time-scale within which the catchment-scale drivers influencing channel form (flow and sediment regimes) could be considered to be relatively steady – allowing the channel cross-section to adjust to a condition of dynamic equilibrium and the channel long-profile to achieve a graded form.

It has only been since fluvial geomorphology has been considered as a 'system science' that the evolutionary and functional approaches to understanding coarse sediment dynamics have been reconciled. Important work by Chorley (Chorley, 1962; Chorley and Kennedy, 1971) and Schumm (Schumm and Lichty, 1965; Schumm, 1973; Schumm, 1977) recognised the potential importance of interacting processes at different scales, which revealed how coarse sediment transport could both explain, and be explained by river channel morphology. Further development of 'systems theory' then led to the recognition of the importance of non-linear system dynamics when attempting to explain process-form relationships and process-response mechanisms in fluvial systems. Recent applications of computational models have been central to improved representations of coarse sediment dynamics, as researchers have taken advantage of the processing power now available to explore complexity in the fluvial system numerically.

This review supports the assertion that the ability to model coarse sediment transport and characterise sediment transfer through the fluvial system from erosional source to depositional sink are critical to understanding, explaining and, therefore, managing morphological adjustments in fluvial systems. In addition, the review also provides the historical framework of established theoretical and empirical approaches to considering coarse sediment dynamics that should underpin the new approach developed in this thesis. Finally, the review emphasises the importance of the temporal and spatial scales involved when considering the most appropriate means of representing the process-form - interrelationships and complex process-response mechanisms within the fluvial system.

At the very least this review provides an introductory context for the scientific topic under investigation within this thesis. In fact, it also offers a basis on which any new approach to catchment-scale coarse sediment dynamics can be both developed and evaluated. Understanding the strengths and weaknesses of different historical perspectives is not only useful when designing a new approach, but also for recognising its strengths and weaknesses. The next stage in the development of a new approach to catchment-scale coarse sediment dynamics is to identify a framework of requirements based upon the data and models currently available to British river management agencies. This will be the focus of Chapter Three.

Chapter Three: Review - data and techniques currently available for assessing catchment-scale coarse sediment dynamics

3.1 Introduction

Chapter Two identified that there is a need to account for catchment-scale coarse sediment dynamics in British river management but that, despite statutory recognition of this, there is currently limited practical application of geomorphological analysis within river management projects. The aim of this chapter is to create a framework of requirements for an approach that quantitatively accounts for catchment-scale coarse sediment dynamics in British rivers and can be both practically and widely applied.

The primary limitation on the applicability of the majority of existing approaches stems from low existing levels of data availability (Lewin and Longfield, 2010). To successfully develop a new approach that is genuinely useful, it is necessary to establish the coverage and assess the accuracy of the data currently used to describe the parameters of interest in practical assessment of coarse sediment dynamics. Therefore, an evaluation of ‘useful’ data currently available for British rivers is performed. This evaluation will assist in designing input data requirements for a new approach that *is* practically applicable at the catchment-scale given existing levels of data availability.

To complete the framework of requirements for the new approach, it is also necessary to identify those features of existing approaches that either limit or enhance their performance and applicability. Therefore, this chapter also evaluates a selection of currently available methods for accounting for coarse sediment dynamics.

3.2 Evaluation of data currently available at the catchment-scale

As identified in Figure 2.11, there are a large number of factors that are of potential interest to studies of coarse sediment dynamics. They fall broadly into two main groups: those describing the nature of flows responsible for transporting coarse material; and those describing the supply of the coarse material and its resistance to transport. These groups can each be subdivided into two further groups. Parameters describing the nature of the flow can be divided into: those influencing the flow hydrograph, and those controlling the flow hydraulics. The nature and supply of coarse sediment can be split into: variables relating to the erodibility of sediment comprising the channel boundaries variables and those that describe the quantity and size of material supplied to the reach in question. These variables are summarised in Table 3.1, with the parameters of interest illustrated in Figure 3.1. The remainder of Section 3.2 will evaluate the available data sources relevant to each of these groups.

Table 3.1 Parameters of interest to studies of coarse sediment dynamics

Nature of flows	Nature and availability of coarse material
Hydrology - Drainage area - Climate - Rock and soil types - Land use / land cover ***Hydraulics*** - Slope (energy slope, water surface slope, channel bed slope, valley slope) - Channel cross-section geometry - Channel roughness (grain roughness, bedform roughness, channel form roughness, vegetation roughness)	***Erodibility of channel*** - Bed material size (Full distribution, Modal, Median - D50, or Mean) - Bed material structure (degree of imbrication / clustering) - Bank material size (Full distribution, Modal, Median - D50, or Mean) - Bank material structure (layering) - Bank vegetation - Artificial erosion protection ***Supply of coarse material*** - Rate of delivery of coarse material from upstream - Rate of delivery of coarse material from landslides / hill-slope coupling - Size of material supplied

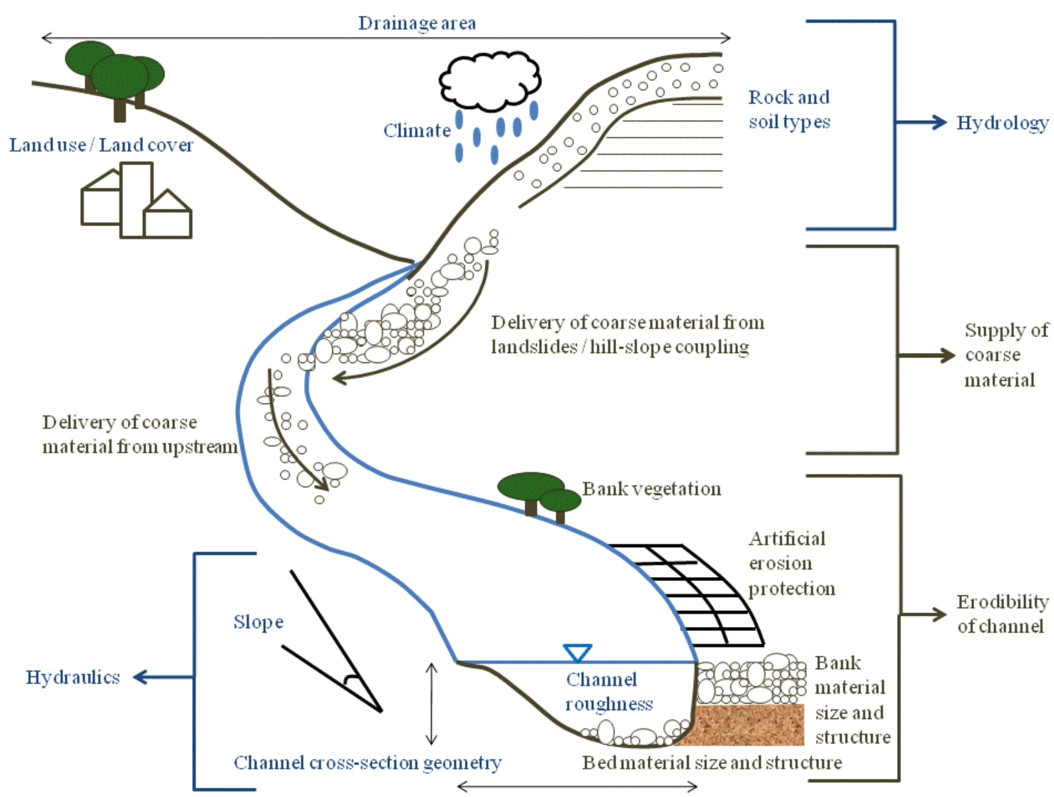

Figure 3.1 Parameters of interest to studies of coarse sediment dynamics

3.2.1 Hydrology

Dominant discharge theory argues that there is a unique flow which, if maintained over a prolonged period, would yield the same channel morphology as that shaped by the natural sequence of flows (Inglis, 1949). It follows that this dominant discharge should be the discharge used in the hydraulic geometry relationships described in Section 2.5.7. However, it was not until Wolman and Miller (1960) published their seminal paper on magnitude-frequency analysis that a rational approach to calculating the dominant discharge was produced. Much of the literature concerning quantification of flows that are important to coarse sediment transport stems from Wolman and Miller's analysis, with the flow doing most work through sediment transport being referred to as the 'effective' discharge and being identified from the product of sediment transport capacity (magnitude) and frequency of occurrence. This effective discharge analysis found that geomorphic events of moderate magnitude are often the most effective (Wolman and Miller, 1960). Whilst initially applied solely to suspended sediment loads, the concept of effective discharge has since been applied to coarse sediment, both in the UK (Carling, 1978), and the US (Andrews, 1980). The magnitude-frequency analysis has become a foundational concept of fluvial geomorphology, with the effective discharge seen as a key metric in the field of river restoration (Shields *et al.*, 2003) and stable channel design (Thorne *et al.*, 1998), that has also been widely adopted in existing river sediment management tools.

However, although attractive, the idea that a single flow can represent the range of flows actually responsible for either the form of the channel or the sediment transported through it is a gross simplification that can never represent the true effect of the range of flows that actually transport sediment. Discharge varies at several temporal scales: within individual events, from an event to event basis, at the seasonal, annual and even long-term scale. Alluvial rivers have the potential to adjust their shape and dimension to all flows that can transport coarse sediment (Lane, 1955a). Both Soar (2000) and Doyle and Shields (2008) argue that, whilst the effective discharge may be the most important to sediment transport, the combined importance of the remaining flows within the distribution that are capable of transporting coarse sediment cannot be neglected. That is, focusing solely on the effective flow fails to consider whether the combined impact of other discharges that are together capable of doing a similar amount of geomorphic work, and hence whether the effective discharge is truly ‘channel forming’. By way of a solution to this conundrum, Doyle and Shields (2008) propose the use of a new metric, the ‘functional-equivalent discharge’, which is the discharge that reproduces the annual mass of sediment load generated by the complete hydrological distribution when all flows produce the same sediment transport rate. Despite the attractiveness of this new metric for those applications requiring a single discharge to represent the entire flow distribution, of more interest to this study is the fundamental point Soar (2000) and Doyle and Shields (2008) raise: that a single discharge is unsuitable for quantifying long term, coarse sediment loads since it represents only the maximum amount of work performed on the channel by a single discharge, rather than the total amount of geomorphic work actually performed by the entire range of sediment transporting flows.

Under circumstances where data defining the time distribution of flow is available it is, therefore, preferable to use this rather than replacing it with a single, representative value. Using the entire flow distribution avoids a serious loss of data and retains the possibility of examining the sediment balance for individual transport events. Examination of Soar’s (2000) work on the Whitemarsh Run restoration project in Maryland, USA helps to elucidate this point. On the analysis of the reach sediment balances for a simulated re-restoration that aimed to create a scheme with a balanced reach sediment budget, Soar (2000) found that there were disparities between sediment supply and capacity within individual flow classes even though the overall flow distribution-based sediment supply and capacity were balanced. These disparities demonstrate the potential for short-term, event-driven perturbations to the channel morphology that are to be expected in river systems in dynamic, meta-stable equilibrium. Further, and perhaps more importantly, they demonstrate that the use of a single representative discharge in a reach-based sediment budget approach cannot fully represent of the sediment balance in that reach.

The most common means of representing the entire flow distribution is *via* a flow-duration curve (FDC). A flow duration curve is constructed from gauged flow data by ranking flows in decreasing order of magnitude and plotting them as a function of exceedence probability (Holmes *et al.*, 2002b). The FDC indicates the percentage of time a given discharge has been exceeded during the period of record at a particular gauging station (Castellarin *et al.*, 2004).

The National River Flow Archive (NRFA) provides access to full records of daily and monthly river flow data from over 1300 gauging stations throughout the United Kingdom (Figure 3.2). The gauging stations are run principally by the Environment Agency for England and Wales, the Scottish Environment Protection Agency and, in Northern Ireland, the Rivers Agency, with the NRFA being maintained by the Centre for Ecology and Hydrology (CEH). This hydrological data is freely available and is easily converted into a flow duration curve for each gauged site. However, the gauge network is sparse and the historic data record relatively short, meaning that the NRFA alone is unable to provide reliable FDCs for many British rivers. In fact, gauged reaches comprise less than 1% of the total length of British rivers (Young *et al.*, 2000). Consequently, in practice it is necessary to generate FDCs synthetically for the vast majority of study locations which fall in ungauged tributaries or main river reaches.

The Low Flow Studies Report (NERC, 1980), developed a standardised approach to producing synthetic FDCs based on the physiographic and climatic catchment characteristics of rivers in Britain. It showed that, when flows are standardised as a percentage of the long-term mean flow, the dependencies on the climatic variability across the country and on the scale effect of catchment area are minimised. The shape of the standardised FDC indicates the characteristic response of a catchment to rainfall. The gradients of standardised, measured FDCs for a range of catchments with different geologies (Figure 3.3) illustrate that impermeable catchments have high gradient curves, reflecting (1) their highly variable flow regimes; (2) their low storage capacity for water, which results in a quick response to rainfall, and; (3) their very low flows in the absence of rainfall. Low gradient FDCs in permeable catchments indicate that the variance of daily flows is low because of the damping effects of groundwater storage provided naturally, for example, by extensive chalk or limestone aquifers. Gustard *et al.* (1992) demonstrated that hydro-geological characteristics are the dominant influence on FDC shape in British rivers; thus, approaches to producing standardised, synthetic FDCs within Britain are based largely on explanatory relationships between FDC shape and catchment hydrogeology.

Figure 3.2 Distribution of NRFA flow gauges within Great Britain. Provided by the Centre for Ecology and Hydrology.

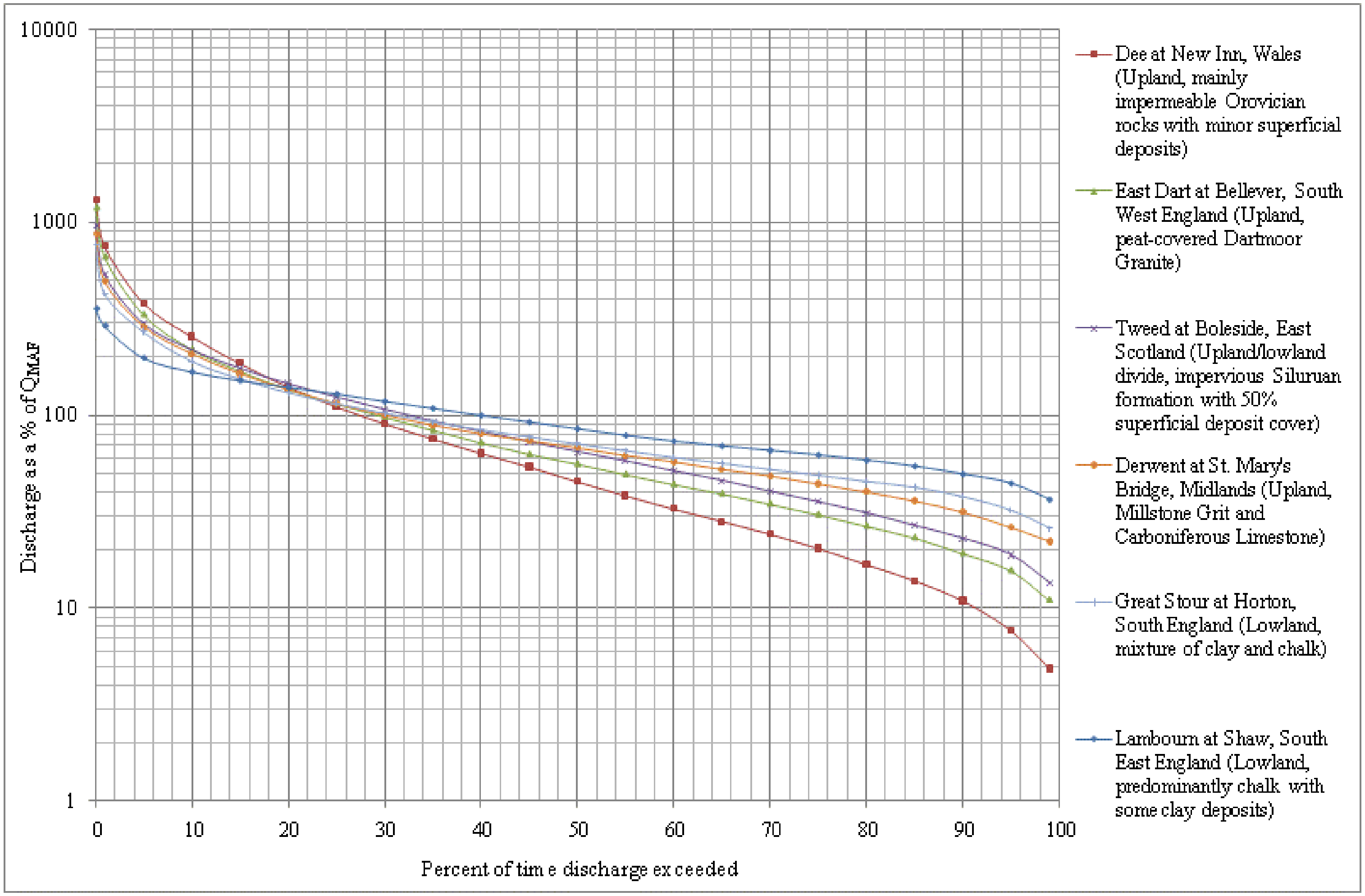

Figure 3.3 Example measured Flow Duration Curves for gauge locations with varying catchment characteristics. Data provided by the Centre for Ecology and Hydrology.

Traditional regionalisation approaches developed for Britain have made use of such observed relationships and developed multivariate regression models between flow statistics and catchment characteristics for Britain under the term ‘Low Flows’ (Gustard *et al.*, 1992). The latest iteration of the ‘Low Flows’-based methodologies is ‘Low Flows 2000’ (Holmes *et al.*, 2002b). ‘Low Flows 2000’ is software that uses a region of influence (ROI) approach to automatically derive a FDC for an ungauged site based on the FDCs observed at ten gauging stations that have catchment characteristics similar to the ungauged site in question. However, whilst it is an ideal data source for representing the hydrology of all channels within Britain, due to software licensing restrictions it has been necessary to consider alternative, but similar, means of estimating flow duration curves for ungauged sites within this study.

In order to derive flow duration curves in a similar manner to ‘Low Flows 2000’ the following data is necessary: catchment drainage area; average annual rainfall; average annual potential evaporation; and hydrogeological soil type. The remainder of this section will explore the availability of this data within British river catchments.

Drainage area for any location in Britain can be obtained using the ‘Hydrological Digital Terrain Model of the UK’ (HDTM) provided by the Centre for Ecology and Hydrology (CEH). This raster dataset provides the drainage area for every 50m grid cell in Britain (Figure 3.4). It is based on a digital elevation model that is processed to derive the catchment drainage network. First, a routing algorithm is applied which determines the flow of water through the catchment by determining the direction of steepest downhill descent using the ‘D8 algorithm’ (Burrough and McDonnell, 2004). This algorithm approximates the flow direction from a DEM grid cell using the steepest downhill slope within a 3x3 window of cells. This results in flow in one of eight different directional values. Based on this process, it is possible to determine the drainage network and the contributing area that flows into each grid cell. However, when a continuous surface like a catchment is approximated by a grid of cells it is inevitable that some cells will be surrounded by neighbours that all have higher elevations (Wechsler, 2006). These *pits* could be real, closed depressions or merely artefacts of the gridding process. They disrupt the routing process and therefore need to be removed in order to represent drainage area. This is either achieved by: cutting through adjacent boundary cells to find the next downstream cell; or increasing the elevation of the cell in question until it is equal to one or more of its neighbours (Wechsler, 2006).

Unfortunately, it is not possible to evaluate the accuracy of the HDTM made available through CEH because of a lack of data with which to ‘ground truth’. It is therefore assumed that, given its position as a standard dataset used by hydrologists, it is suitable for estimations of catchment drainage area.

Average annual rainfall throughout Britain is obtainable as a digital raster dataset through the Centre for Ecology and Hydrology. It is based upon monthly rainfall measurements from 1961-2007 which have been integrated to yield a 46 year average annual rainfall depth for every 1km grid cell in Britain (Figure 3.5). As with the HDTM dataset, it is not possible to evaluate the accuracy of the rainfall data made available through CEH because of a lack of data with which to ‘ground truth’. Once again, therefore, it is assumed that given its position as a standard dataset used by hydrologists, it is suitable for estimations of catchment drainage area.

Average annual potential evaporation values for any location within Britain can be estimated using the Meteorological Office’s ‘Meteorological Office Rainfall and Evaporation Calculation System’ (MORECS). Unfortunately, due to licensing restrictions this was not available for this study. However, Grindley (1970) published much of the progress made by researchers from the Meteorological Office on the estimation and mapping of evaporation in the United Kingdom. Based on his scaled map of average annual potential evaporation for England and Wales, it was possible to derive a digital raster dataset for use in this study. This was achieved by geo-rectifying Grindley’s original map, digitising the contours and interpolating between them to produce Figure 3.6. Again, because of a lack of data with which to ‘ground truth’, it has not been possible to evaluate the accuracy of this data.

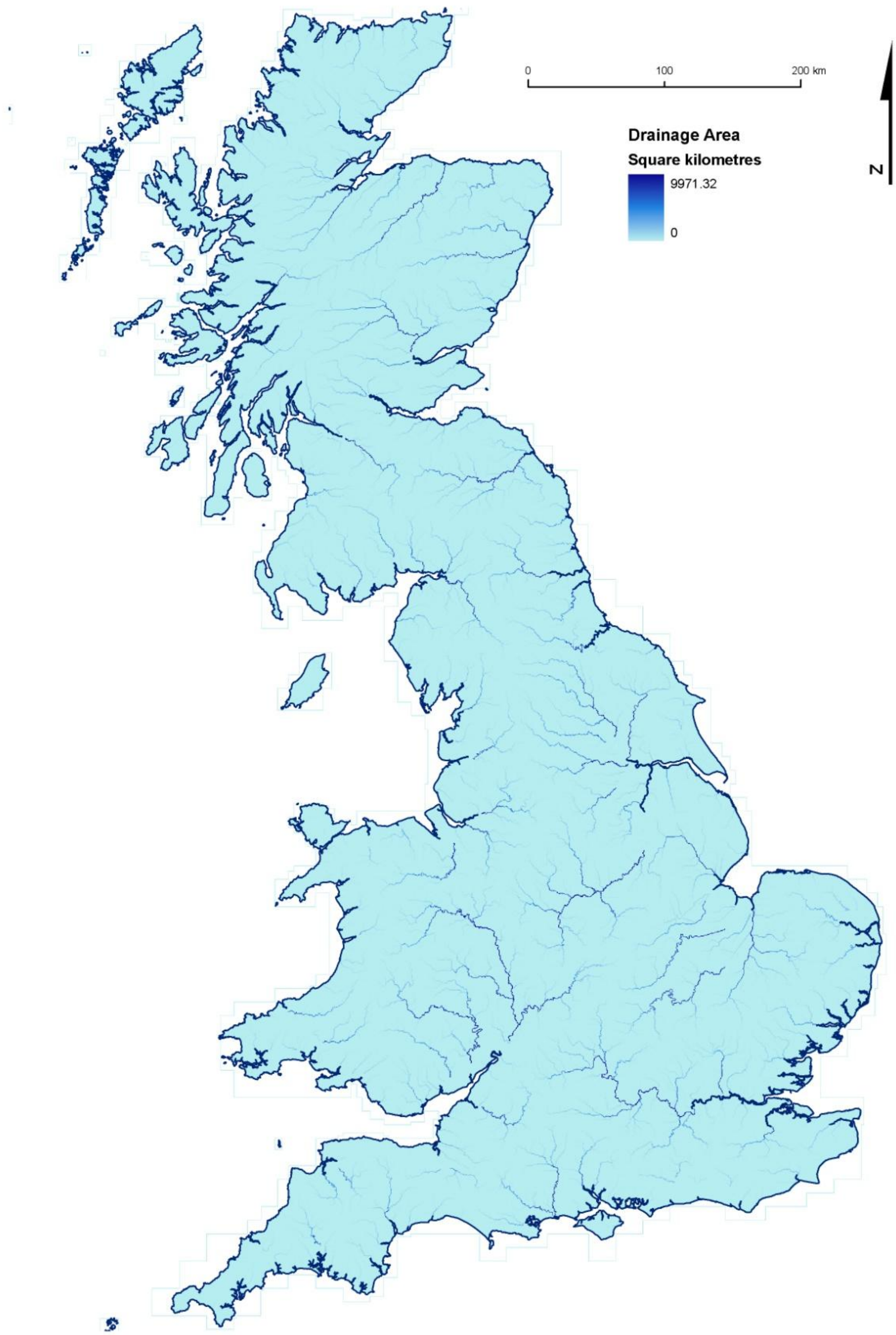

Figure 3.4 Hydrological Digital Terrain Model (HDTM) for Great Britain. Provided by the Centre for Ecology and Hydrology.

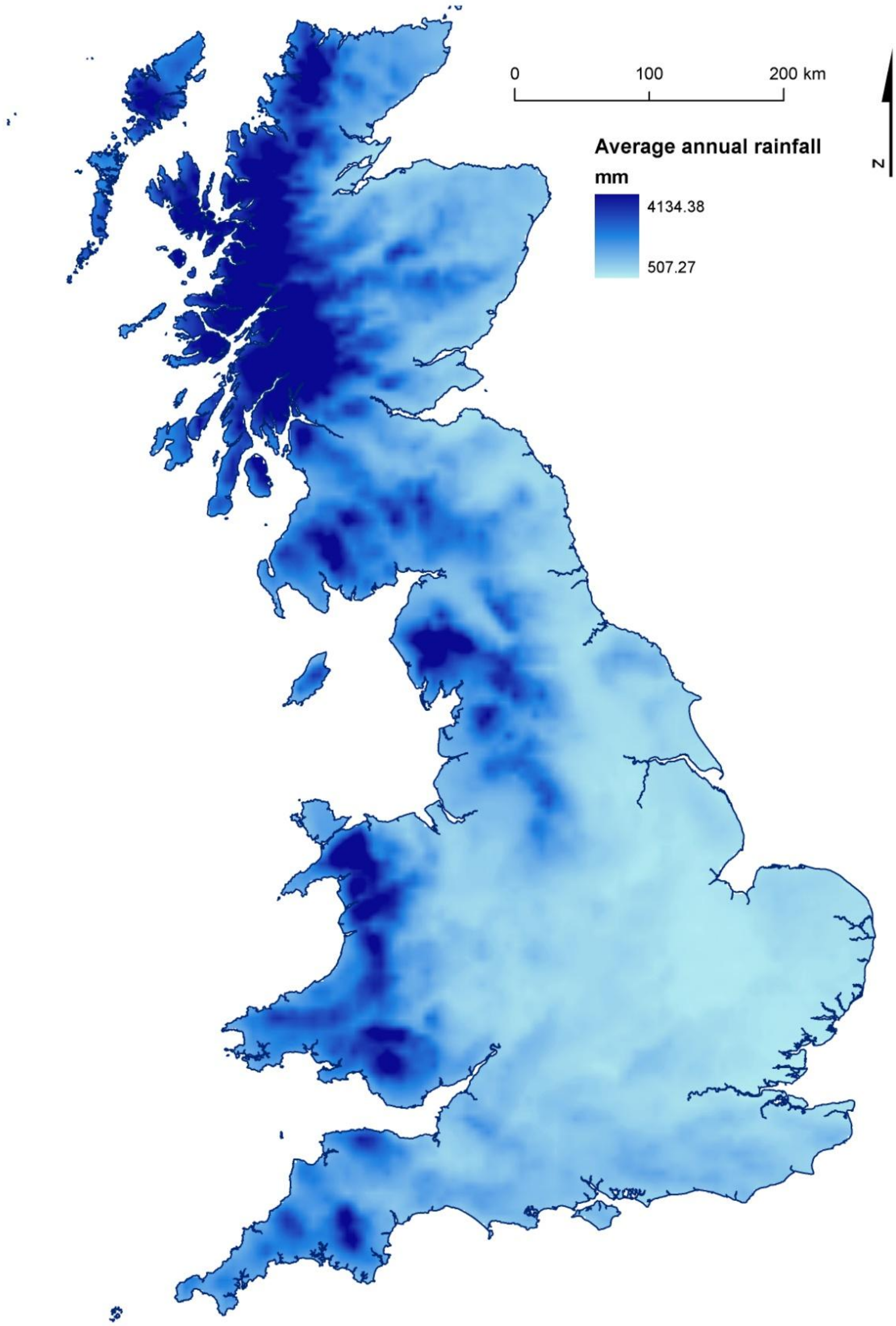

Figure 3.5 Average annual rainfall in millimetres for Great Britain. Provided by the Centre for Ecology and Hydrology.

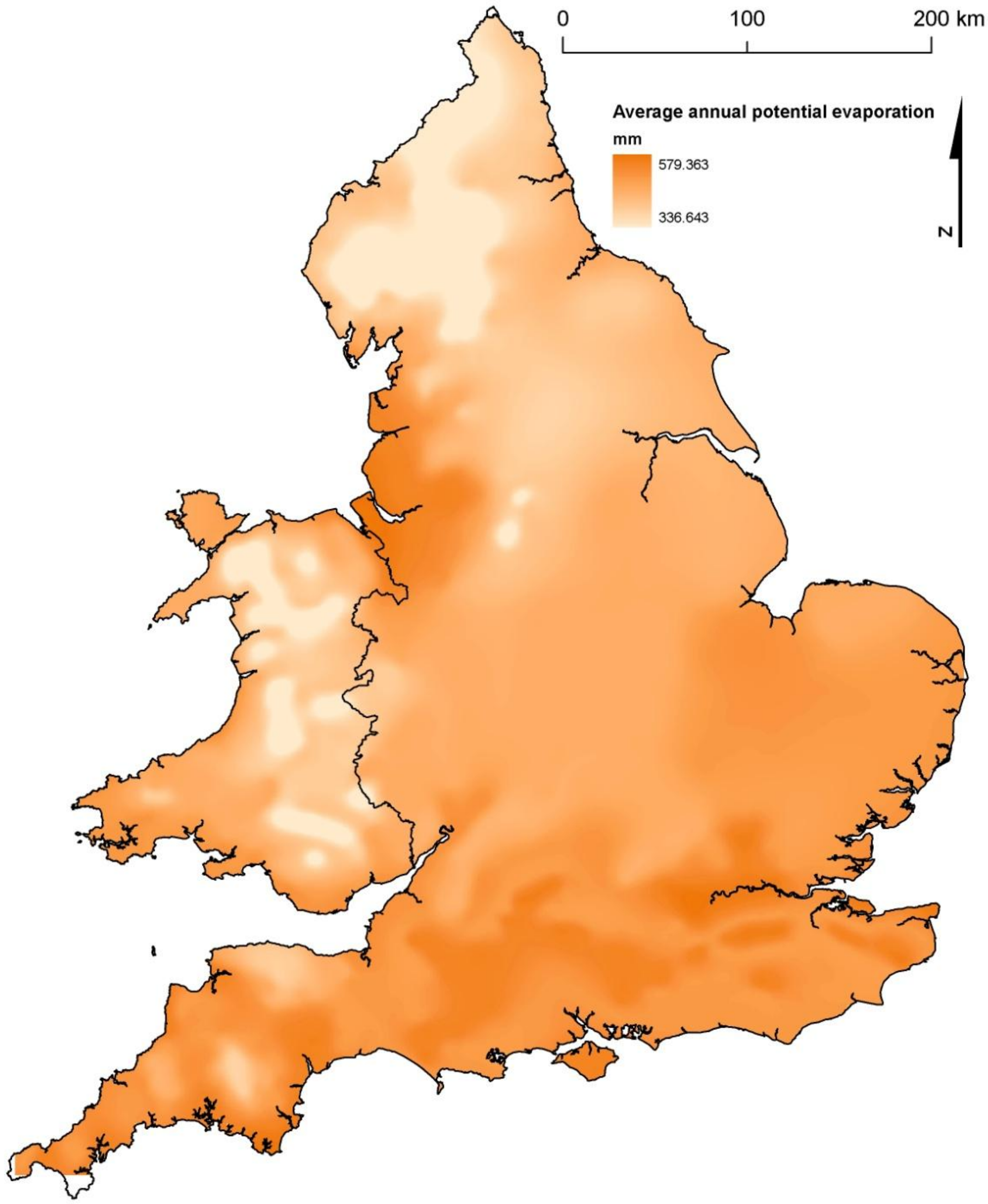

Figure 3.6 Average annual potential evaporation in millimetres for England and Wales. Digitised from Grindley (1970).

Hydrogeological soil type data for the entire of Great Britain was developed originally by Boorman *et al.* (1995) as part of a research project for the Institute of Hydrology. In their study, Boorman *et al.* (1995) developed a hydrologically-based classification of the soils of the United Kingdom. The classification was based on conceptual models of the processes that occur in the soil and the underlying substrate. The resulting scheme is known by the acronym HOST, standing for Hydrology of Soil Types. HOST has 29 classes, with soils assigned to classes based on their physical properties and the hydrogeology of their substrate. Digital copies of this dataset are available through the National Soils Research Institute, and the Macaulay Land Use Research Institute, for England and Wales, and Scotland respectively.

Despite the lack of evaluation of the individual datasets, some indication of their accuracy and utility can be taken from the results of Young *et al*. (2000). Young *et al*. (2000) applied each of the datasets described above within the 'Low Flows' methodology and achieved what they deemed to be an acceptable level of accuracy when predicting the mean annual flow (Q_{MAF}), and the flow exceeded 95% of the time (Q_{95}) for the dataset used to construct the model (factorial standard error of 22% and 55% respectively).

This review of available hydrology data is used within Section 6.6.2, where the methodology for estimating flow duration curves within the new approach for quantitatively accounting for catchment-scale coarse sediment dynamics is described.

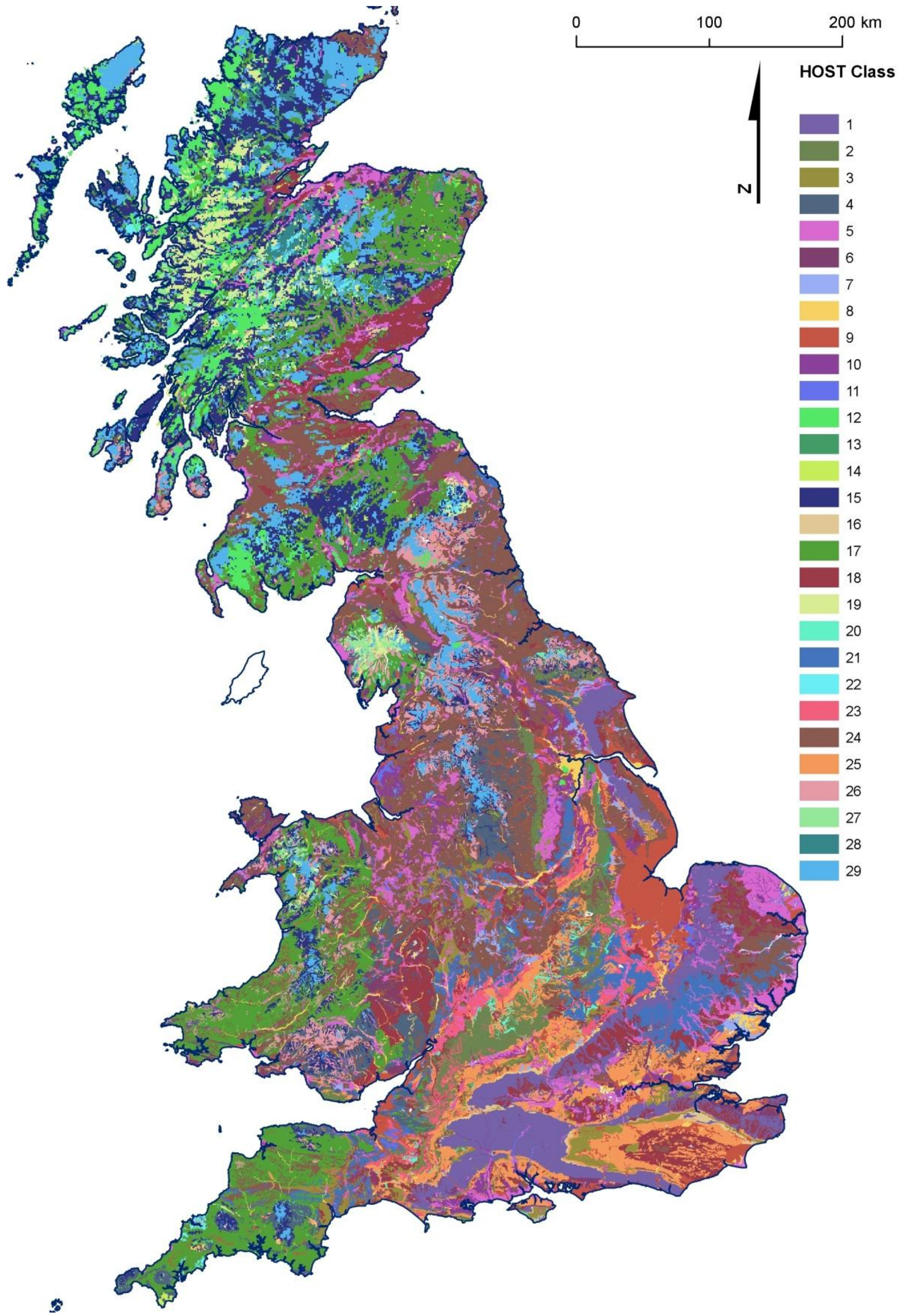

Figure 3.7 Hydrology of Soil Types classification for Great Britain. Provided by the National Soils Research Institute for England and Wales, and the Macaulay Land Use Research Institute for Scotland.

3.2.2 Hydraulics: cross-section geometry

The cross-sectional form of natural channels is characteristically irregular in outline and locally variable. When considering small-scale channel changes, detailed representation of channel morphology is justified since, whilst morphological changes are generally driven by catchment-scale processes, the impact that these broad-scale processes have on local channel change is influenced by local morphological controls on erosion and deposition. This was clearly demonstrated by Ashworth and Ferguson's (1986) exploration of the complex interactions between spatial and temporal variations in channel morphology velocity and shear stress, bed-load transport rate, and bed-load and bed material size distribution (Figure 2.10). Ashworth and Ferguson's (1986) findings were later supported by Lane and Richards's (1997) study of erosion and deposition patterns in a reach of the Borgne d'Arolla River in the Swiss Alps where they found that local channel morphology determined the manner in which sediment supply and discharge fluctuations interacted to control the form of channel change within the reach. However, despite Lane and Richards's claim that channel morphology has an important effect on the ability of a reach to move sediment, others have argued that, for situations where a process has a characteristic time-scale which is much shorter than the time-scale of interest, representation of channel morphology may be 'relaxed', although not ignored (Church and Mark, 1980). It is this latter line of thought that justifies some approaches to coarse sediment dynamics simplifying representations of channel section morphology when accounting for catchment-scale processes over extended time periods.

Whether or not detailed channel morphology is considered important in influencing broad-scale coarse sediment dynamics, consistent, widespread surveys of channel cross-section are currently unavailable throughout British rivers. The Environment Agency's 'Section 105' surveys, so-called due to their conception from the needs of Section 105(2) of the Water Resources Act 1991, have limited coverage within Britain, and surveys performed by private consultancy firms on behalf of the Environment Agency are generally site specific with little effort made to compile a national database. As identified above, whilst detailed channel morphology is critically important for analysis of morphological change over short time- and space-scales, when considering sediment dynamics at the catchment-scale it is justifiable to simplify representations of channel morphology. Nevertheless, as argued by Lane and Richards (1997), channel morphology still influences broad-scale system behaviour and therefore alternative means of representing channel cross-section dimensions are necessary.

One potential solution to this problem involves adopting the principles of ‘hydraulic geometry’ introduced in Section 2.5.7. As downstream hydraulic geometry relations provide a quantitative description of how channel width and depth vary with changing discharge, it is possible to predict a channel’s dimensions based on a representative discharge using relations similar to those in Equation 2.11 and Equation 2.12 that were derived by Leopold and Maddock (1953).

Numerous hydraulic geometry studies in a variety of environmental settings have since widened the potential range of the exponents in Equation 2.11 and Equation 2.12 from those originally derived by Leopold and Maddock (1953). Values of b and f have been found to range from 0.39 to 0.6, and 0.29 to 0.4 respectively (Ming, 1983), although they have been summarised as falling most frequently in the range 0.4 to 0.5, and 0.3 to 0.4 respectively (Park, 1977; Rhodes, 1987). The cause of this variation lies in the dependence of hydraulic geometry relations on a range of environmental factors including climate, physiography and geology (Park, 1977). Therefore, if hydraulic geometry relationships are to be considered within the context of this thesis then they should be based on environments specific to British rivers such as those developed by Nixon (1959):

$$w = 2.99{Q_{bf}}^{0.5}$$

Equation 3.1

$$\bar{d} = 0.55{Q_{bf}}^{0.333}$$

Equation 3.2

where Q_{bf} is bankfull discharge, which Nixon equated with the flow exceeded 0.6% of the time.

However, there is a fundamental problem with using cross-section geometry derived from empirical hydraulic geometry relationships within assessments of coarse-scale sediment dynamics. Almost by definition, hydraulic geometry relationships describe the condition of a channel when it is in some form of averaged state, potentially near equilibrium. Therefore if, when accounting for coarse sediment dynamics channel geometry is defined by hydraulic geometry relationships, it will most likely result in the channel being identified as in equilibrium. For example, in reality the channel may be wider than predicted by hydraulic geometry relationships and it would therefore experience deposition and channel narrowing. Further, because they are based on averaged conditions, traditional hydraulic geometry relationships generate an artificially smooth representation of downstream changes in channel morphology. As a result, they are generally insensitive to variations in the downstream trend that are important to catchment-scale coarse sediment dynamics. Whilst some efforts have been made to generate hydraulic geometry relationships that vary continuously with explanatory variables other than discharge (Rhoads, 1991), their predictions remain inherently based upon an assumption of equilibrium form. As a result, channel geometries based upon hydraulic geometry relationships will result in conditions that are artificially biased towards equilibrium and therefore do not represent instabilities that may be of interest.

A second source that could potentially provide information on channel cross-section geometry throughout British rivers is the Environment Agency's River Habitat Survey (RHS) database. The RHS is a system for assessing the character and habitat quality of rivers based on their physical structure (Raven *et al.*, 1998b). It has four distinct components: (i) a standard field survey method; (ii) a computer database, for entering results from survey sites and comparing them with information from other sites throughout the UK and Isle of Man; (iii) a suite of methods for assessing habitat quality; and (iv) a system for describing the extent of artificial channel modification. The RHS field method itself is a systematic collection of data associated with the physical structure of watercourses. Data collection is based on reaches that are a constant 500m in length. Map information is collected for each 500m reach and includes grid reference, altitude, slope, geology, height of source and distance from source. During the field survey, features of the channel (both in-stream and banks) and adjacent river corridor are recorded. Channel substrate, habitat features, aquatic vegetation types, the complexity of bank vegetation structure and the type of artificial modification to the channel and banks are all recorded at each of 10 'spot-checks' located at 50 m intervals. A 'sweep-up' checklist is also completed to ensure that features and modifications not occurring at the spot checks are recorded. Cross-section measurements of water and bankfull width, bank height and water depth are estimated at one representative location to provide information about geomorphological processes acting on the channel. The number of riffles, pools and point bars found in the site is also recorded. In all, more than 200 compulsory data entries are made at each site, collectively building a comprehensive picture of habitat diversity and character (Raven *et al.*, 1998b).

Despite its primary purpose as a means of assessing habitat quality and naturalness, and because of the lack of alternative official data collection systems for parameters relating to channel morphology, the data provided by the RHS provides the first major coverage of channel geometry for British rivers (Newson *et al.*, 1998). Whilst not a geomorphological survey, in order to fulfil its primary objective of recording habitats a basic awareness of river processes and features was required within the RHS. Therefore, some consideration of geomorphological features that would be both diagnostic of wildlife habitat quality and of benefit to geomorphological research was given in its design (Newson *et al.*, 1998). Incorporated within the RHS are the following broad categories of geomorphological information:

- topographic information from maps, e.g. altitude, slope and planform;
- photographic information (site photographed at time of survey);
- qualitative information on basic form, e.g. valley shape, naturalness of channel;

- qualitative information on detailed form, e.g. bank profiles;
- observed (not measured) channel dimensions, e.g. bankfull height, width;
- qualitative description of boundary materials, e.g. bank material, bed material;
- bank features, e.g. eroding cliff;
- natural channel features, e.g. riffles, bars (numbers, not size, location); and
- artificial channel features, e.g. piling, gabions.

Since the RHS was first conceived in 1994, over 17,000 surveys have been completed, resulting in an impressive collection of information on British rivers (Figure 3.8A). However, the coverage of British river catchments is by no means consistent (Figure 3.8B compared with Figure 3.8C), which creates practical difficulties for any approach that attempts to use RHS data within a large number of British river catchments. Further, the RHS reaches are designed to be a statistical sample of the habitat conditions observed within different types of river reaches throughout Britain. As a result, the RHS cannot be treated as a continuous representation of channel morphology within a river catchment. Channel width and depth vary continuously both within and between RHS sampling reaches, and this becomes notably problematic when representing channel morphology in river catchments with very few RHS sampling reaches (Figure 3.8C). This means that RHS data are not sufficient to provide the continuous coverage of the entire British river network that would be ideal for widespread catchment-scale assessment of coarse sediment dynamics.

A final alternative source of channel geometry data for British rivers is through the UK Ordnance Survey's mapping data. OS MasterMap is the latest generation of mapping products produced by the Ordnance Survey and replaces prior vector-based spatial databases such as OS Land Line (OS, 2001). In MasterMap, a line object is used to define the position of a river where its width is less than 1 metre in urban areas and 2 metres in rural, mountainous and moorland areas. Where the river width exceeds these limits, it is represented as a polygon (Figure 3.9). The width of the polygon is, somewhat ambiguously, defined as the width at the normal winter level (OS, 2001).

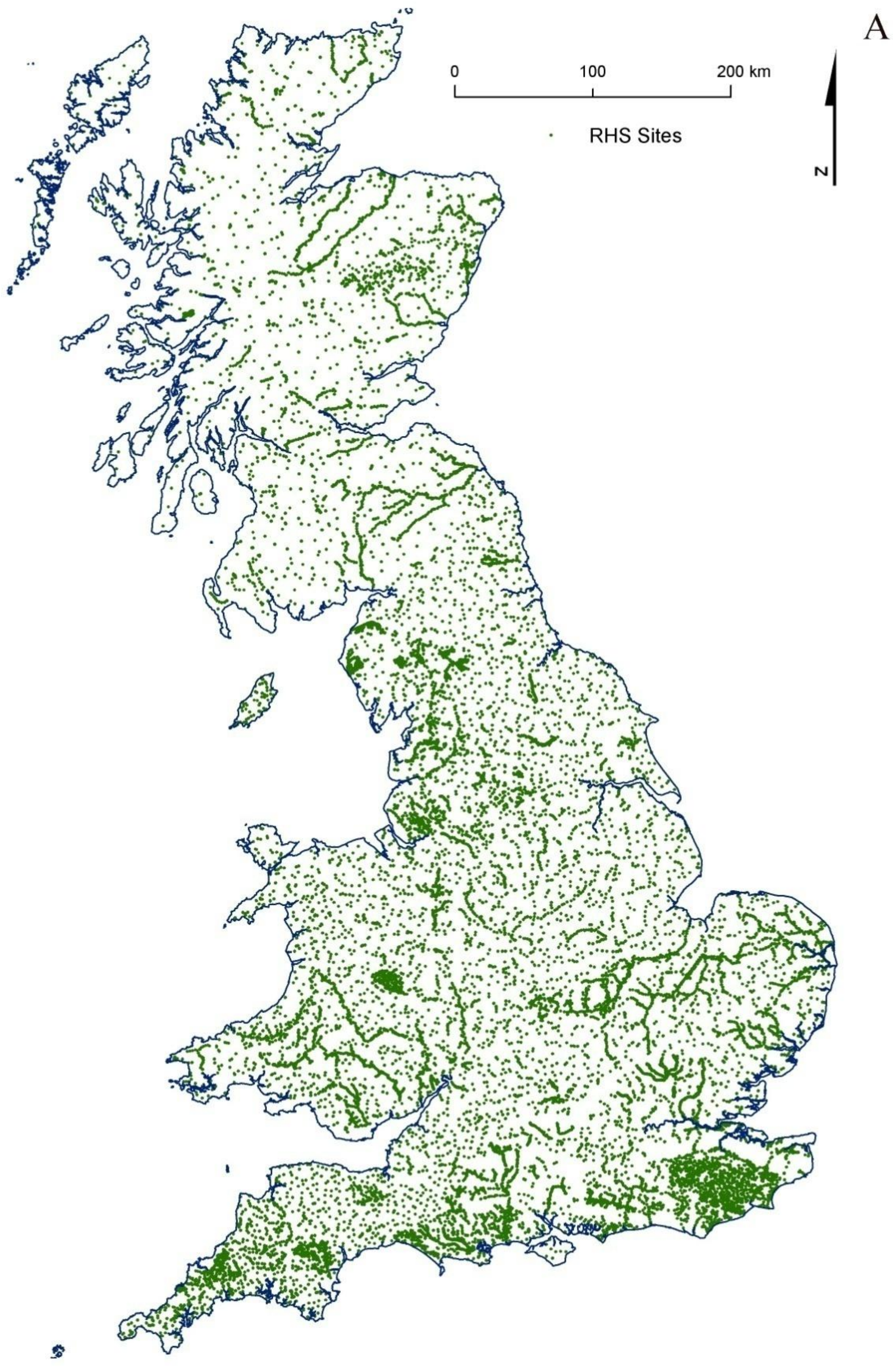

Figure 3.8 (A) Distribution of surveyed RHS sites within Great Britain.

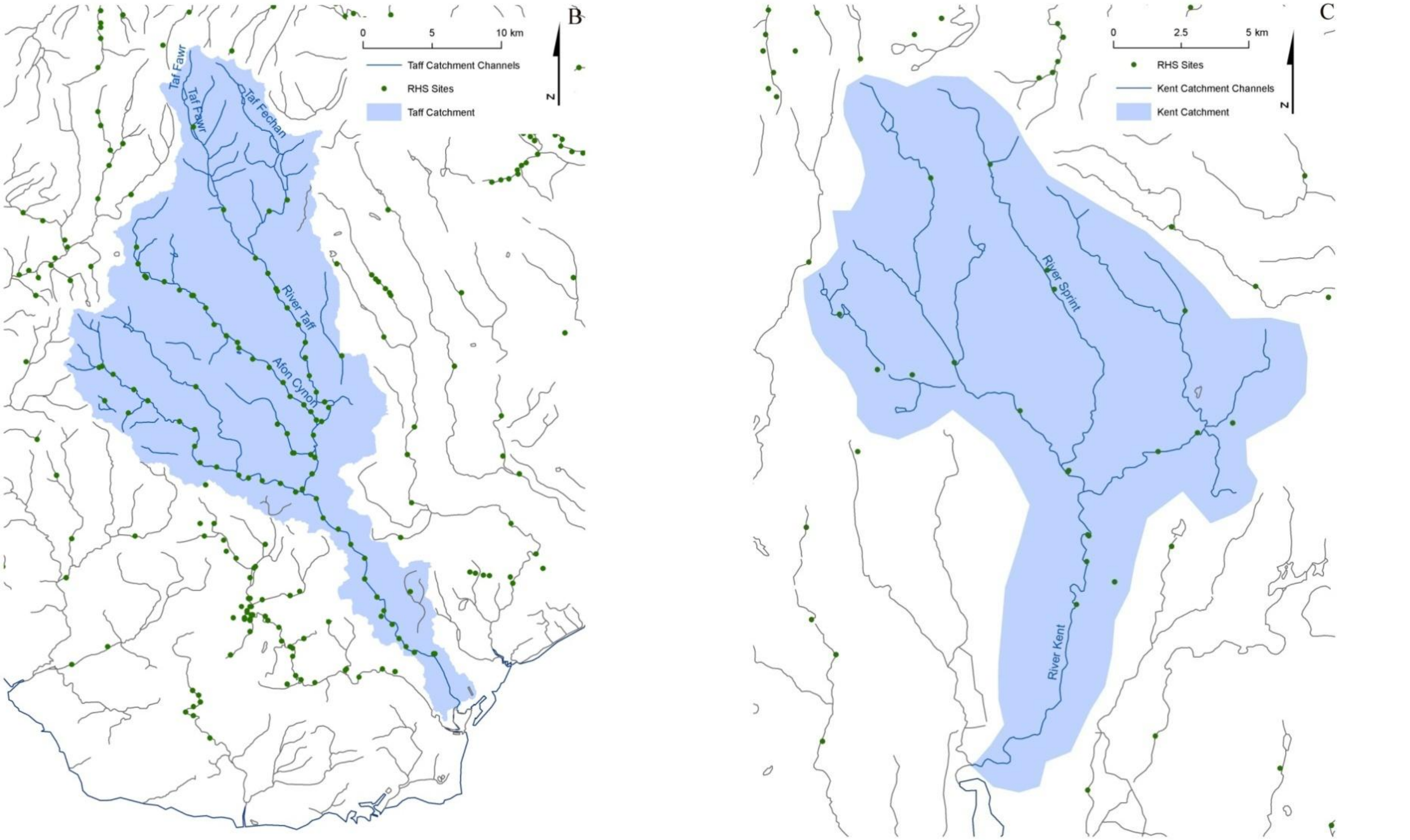

Figure 3.8 (B) Distribution of surveyed RHS sites within the Taff catchment, South Wales. (C) Distribution of surveyed RHS sites within the Kent catchment, Cumbria.

Assessment of the accuracy of widths represented by OS MasterMap was undertaken by Barker (2008). Barker (2008) took a series of bankfull channel width measurements along the River Alne in Warwickshire and the upper reaches of the River Severn in Wales and compared them with the widths represented by the OS MasterMap data. The results are replicated in Figure 3.10. For the River Alne, it can be seen that there is a tendency for width to be greater when measured in the field than with the MasterMap data, with differences being the greatest in the headwaters and reducing downstream. The normal winter level, the definition for MasterMap channel width, should be less than the measured bankfull channel width if the common assumption that channel forming flows have a recurrence interval of approximately 2 years is correct.

The relationship between MasterMap width and field measured widths on the River Alne is not parallel with the 1:1 line plotted in Figure 3.10A. This indicates that error changes with the magnitude of the width values. After combining the River Alne data with the measurements taken on the River Severn, Barker (2008) observed that a much-improved relationship exists between field measured and MasterMap widths. Whilst still not a perfect agreement, 97% of the variation in field measured width is explained by the MasterMap data, and the slope of the line suggest a near 1:1 agreement (0.978). Therefore, OS MasterMap data can be used to inform channel geometry within systems that account for catchment-scale coarse sediment dynamics in British rivers, although it should be noted that the accuracy of MasterMap width measurements has been shown to deteriorate within smaller channels (Barker, 2008).

This review of available cross-section geometry data is used within Section 6.6.4, where the methodology for parameterising channel widths within the new approach for quantitatively accounting for catchment-scale coarse sediment dynamics is described.

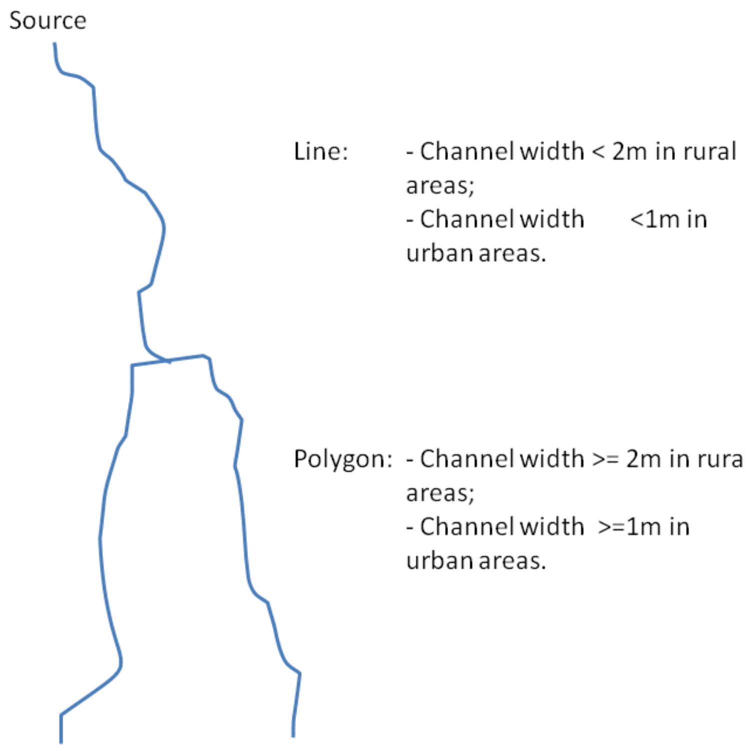

Figure 3.9 Representation of channel widths in MasterMap. (A) MasterMap representation of channel width at the confluence of the Afon Einon and Afon Banwy, mid-Wales. (B) Application of lines and polygons to represent channels of different widths within MasterMap.

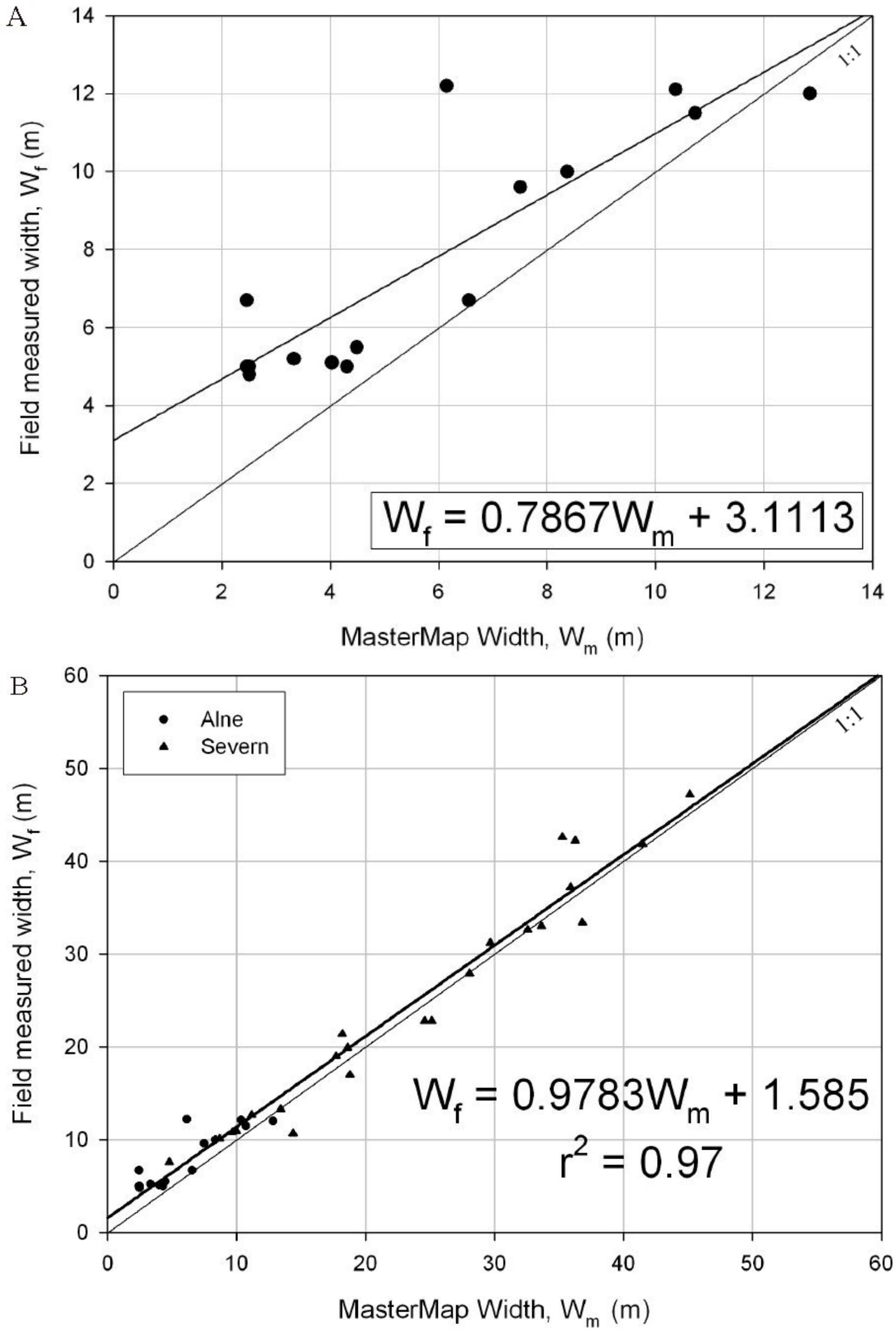

Figure 3.10 Relationship between widths measured using MasterMap and field procedures, (A) for just the River Alne: $r^2 = 0.76$; $p < 0.0001$, and (B) for the Rivers Alne and Severn: $r^2 = 0.97$; $p < 0.0001$. Taken from Barker (2008).

3.2.3 Hydraulics: slope

Channel slope is the change in channel elevation per unit distance downstream. Since the mechanical energy responsible for mobilising flowing water is generated as a result of the release of the water's potential energy as it moves down-slope, the gradient has important consequences for the energy of the stream flow and the potential to transfer coarse sediment. The 'energy slope' describes the expenditure of energy within the water column with respect to distance downstream (Chow, 1973), but channel slope is often used as an approximation based on an assumption of uniform flow (Ferguson, 2005). The key issue in selecting a means of representing slope revolves around scale. Some studies (Lawler, 1992a; Knighton, 1999) have experimented with the use of functional equations to provide a simplified representation of the slope of longitudinal river profiles across entire catchments. However, these have often been found to be limited, as demonstrated on the River Trent, UK by Knighton (1999). In this case, Knighton (1999) found that the slope values taken from profile equations had important differences to those observed in reality due to the importance of local-scale variation. Knighton's (1999) findings are supported by Fonstad's (2003) work in the Costilla basin in the central Sangre de Cristo Mountains, New Mexico, where he found that hydraulic geometry relations for slope significantly under-predicted the channel slope in the upper catchment and failed to predict important longitudinal nick-points and scarps in the profile.

On the other hand, delineating slope at too high a spatial resolution can also be unsuitable for sediment analysis at the catchment-scale. When using high-resolution measurements of slope, there are questions regarding the importance of the local variations in bed elevation caused by bed forms, such as riffle/pool and step/pool formations, for broad-scale sediment dynamics. This issue is similar to that raised in Section 3.2.2, where questions were raised regarding the importance of local-scale variations in channel morphology in assessments of catchment-scale coarse sediment dynamics. As above, it is considered here that the effects of small-scale slope variations caused by local bed topography may not be totally insignificant within catchment sediment dynamics, but their inclusion can distract from macro-scale slope changes that play a more important role within catchment-scale sediment dynamics. It is therefore necessary to obtain accurate representations of channel slope at a scale suitable for assessing catchment-scale sediment dynamics.

The RHS database introduced above contains a quantification of channel slope for the surveyed reach estimated from map based data (Newson *et al*., 1998). However, there are issues regarding the accuracy and consistency of these slope values and, considering the important role of slope in driving coarse sediment dynamics, a more accurate data source is necessary. The obvious solution to this is to derive channel slope from Digital Elevation Models (DEMs) using a Geographical Information System (GIS).

Finlayson and Montgomery (2003) describe their application of DEMs in calculations of channel slope and highlight an important issue regarding the grid resolution of the DEM used. They found that a reduction in the grid cell resolution used can cause an artificial decrease in the variability of derived slope measurements as coarser grid sizes cannot resolve fine landscape features. Application of DEMs within topographic modelling is also strongly dependent on the vertical resolution of the data. DEMs that measure elevation to the nearest metre generally create stepped profiles and result in poor representations of slope. It is therefore important to obtain slope measurements from a DEM with as high a horizontal and vertical resolution as possible, and then re-sample to a coarser spatial resolution if necessary.

The highest resolution DEMs that are currently widely available in Britain are derived from LiDAR (Light Detection and Ranging), which is an airborne mapping technique which uses a laser to measure the distance between the aircraft and the ground at spatial resolutions of up to two metres. The Environment Agency (EA) has purchased its own LiDAR system, which it has installed in a survey aircraft along with its other operational remote sensing instruments to survey catchments of interest to flood risk management within the UK. The EA LiDAR dataset represents the most accurate remotely sensed source of elevation data available, with a vertical RMSE (Route Mean Squared Error) of +/-0.15m, and horizontal RMSE of +/-1m. Whilst not providing a complete coverage of all river catchments in Britain, the Environment Agency's dataset does cover the majority of significant river channel paths in England and Wales, enabling the calculation of channel slope for the majority of British rivers (Figure 3.11). The horizontal resolution of the EA's LiDAR data varies from 0.15m to 2m grid cells (Figure 3.11).

Other potential sources for channel slope measurements include the NEXTMap Britain Digital Elevation Model, which was derived using interferometric synthetic aperture radar (IfSAR). It operates in a similar manner to LiDAR except that it uses radio waves instead of light waves. This dataset has the advantage that, because IfSAR technology allows large areas to be mapped efficiently and independently of weather conditions, there is a much more consistent coverage across Britain. The NEXTMap data are available at a horizontal resolution of 5m grid cells. Dowman *et al.* (2003) found that in flat areas the NEXTMap Britain DTM has a vertical accuracy of +/-0.6m RMSE and in hilly terrain a vertical accuracy of +/-2.64m RMSE. Whilst the best approximation to the elevation of the surface is in open areas such as floodplains, it has been found that accuracy of slope measurements increases in steeper areas because of the greater differences in elevation (Lane and Chandler, 2003).

A final potential source of slope data is the Ordnance Survey Landform Profile DTM which is available for all of Britain. This data is based on a combination of photogrammetry, where height values are measured based on photographic images, and topographic survey. The horizontal resolution of these data are 10m grid cells. The OS Landform Profile DTM was originally available in the form of contour maps, with a vertical spacing of 5m in lowland areas and 10m in mountainous / moorland areas. Since these contour maps have been converted into DEMs they offer a vertical accuracy of +/-2.5m RMSE and +/-5m RMSE in lowlands and mountains respectively.

There are a variety of methods for calculating slope from the digital elevation models described above. Past researchers have applied a fitted curve, generally in the form of an exponential function, to represent slope at the catchment-scale (Lawler, 1992a; Knighton, 1999). Other researchers who have used DEM models to calculate slope have investigated the potential of both vertical- and horizontal-slice measurement approaches (Reinfelds *et al.*, 2004; Jain *et al.*, 2006) The three different approaches that have been considered in this study are based on: i) curve fitting, ii) a horizontal slice approach, and iii) a vertical slice approach.

Curve fitting approaches to slope representation are generally in the form of simple exponential models of channel long profiles generated either theoretically (Rana *et al.*, 1973; Lawler, 1992a), or empirically (Knighton, 1999; Jain *et al.*, 2006) and typically in the form:

$$E = a \cdot e^{-b \cdot L}$$

Equation 3.3

with long profile slope approximated by:

$$S = (-)b \cdot a \cdot e^{-b \cdot L} = k \cdot e^{-b \cdot L}$$

Equation 3.4

where E is elevation above a datum (m), S is slope, L is downstream distance (m), S_0 is the initial slope, and b is the coefficient of slope reduction. This type of function describes slope as being steepest in the headwaters and becoming shallower at a decreasing rate with distance downstream. This is considered by some to represent the long profile of fluvial systems that are adjusted to a 'graded' condition (Lawler, 1992a; Knighton, 1999), a concept that dates back to the work by Davis and Gilbert explored in Section 2.5, and refers to a state where a river channel's morphology is adjusted so that its flows can convey precisely the amount of sediment delivered to it from upstream. Barker (2008) found that, when applied to a selection of 34 British rivers, the exponential function explained over 83% of the variation in slope in all cases, with 23 of the sampled rivers having over 95% of the variation in slope explained by an exponential function.

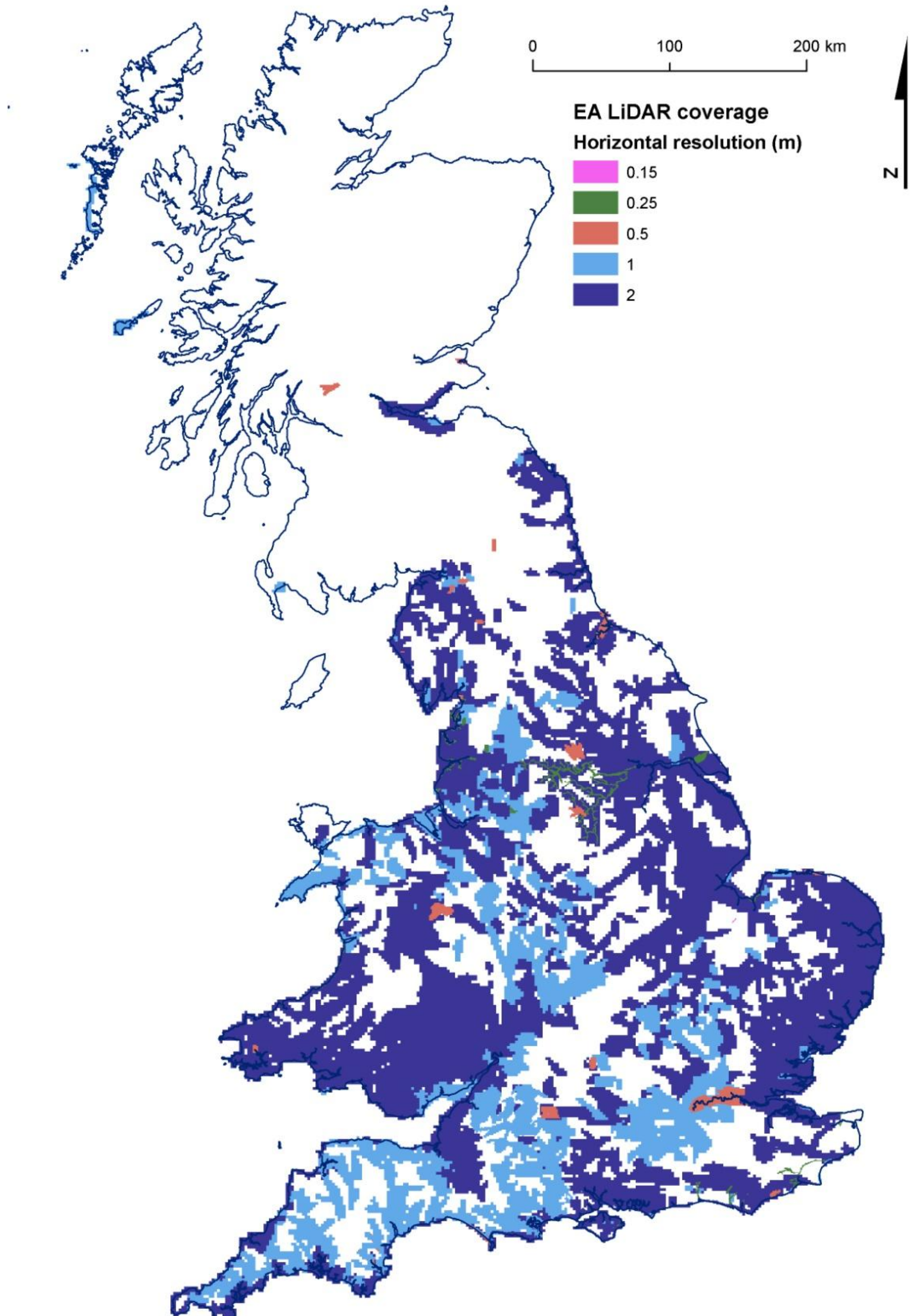

Figure 3.11 Location and resolution of Environment Agency LiDAR data coverage across Great Britain.

However, despite the high levels of statistical explanation, fitted curves fail to represent local variations in slope present within natural long profiles. In a similar manner to hydraulic geometry representations of channel morphology discussed in Section 3.2.2, using a consistent trend to represent slope neglects the discrepancies in slope that are important in generating discontinuities in coarse sediment transfer within natural river systems. In his application of exponential curves to 34 British rivers, Barker (2008) found that, despite high levels of statistical explanation, the fitted curves failed to identify important local increases and decreases in slope. These findings echo those of Harmar and Clifford (2007), who demonstrated that, although the long profile of the Lower Mississippi River is concave at the catchment-scale, the profile is characterised by local discontinuities and shorter trends. Harmar and Clifford (2007) showed that this variability is a response to morphological and bed material changes relating to a range of natural (geological, tectonic, tributary input) and engineering controls. Based on this they argued that a concave river profile is a property that emerges from several scales of process–form interaction.

As a result of similar findings in the River Trent catchment, Knighton (1999) suggested that assessments of downstream variation in parameters like stream power and sediment transport capacity should be based on cartographically measured slopes rather than slopes derived from fitted curves, because the latter do not always adequately represent local variations in gradient.

Horizontally sliced slope measurements involve cartographically measuring slope over a regular downstream distance (d) as demonstrated by Reinfelds *et al.* (2004) and Jain *et al.* (2006). Slope is calculated by dividing the height drop between two points by the downstream distance between them, with the slope value attributed to a point halfway between them:

$$S_n = \frac{E_{n-{d}/{2}} - E_{n+{d}/{2}}}{d}$$

Equation 3.5

where S_n is the slope at a point a certain distance, n ,downstream, and d is the distance over which slope is measured (Figure 3.12).

One potential limitation with horizontal slice approaches to slope measurement is the occurrence of zero, or flat slopes. Since digital elevation models have a limited vertical resolution, if a height drop is not achieved over the specified slice length then the measured channel slope value is zero. As it is often necessary to assume that channel and energy slope are parallel, and because a zero energy slope value is physically unrealistic, zero slope values need to either be avoided or removed from the analysis.

Barker (2008) demonstrated how measured slope changes over horizontal slice lengths of 0.1 to 30km. This analysis demonstrated that the range of slope values for a particular river decreases as the horizontal slice width increases so that increasing the horizontal slice width has a smoothing effect on the overall slope profile. As a result, if the slope measurement interval is too short then the scatter in the longitudinal profile is high and detecting the general downstream trends is difficult; but if the slope measurement interval is too great then the slope profile is smoothed so general catchment trends can be detected but potentially important within-basin variations in slope are lost or dampened.

Barker's (2008) analysis also demonstrated that as horizontal slice width is increased, the number of zero slope values decreases. This is because increasing the distance over which slope is measured increases the likelihood of a measurable decrease in elevation. A final consequence of varying the horizontal slice width identified by Barker (2008) is that the number of slope measurement points is reduced as the slice width is increased. This is because slope is measured at the midpoint of the horizontal slice, and so slope can neither be calculated for the first half of a slice length of the elevation sequence, nor for the last half of a slice width at the end of the elevation sequence.

Based on consideration of the above factors, and analysis of a number of test datasets, Barker (2008) concluded that a horizontal slice width of 1 km provided a compromise between the high scatter and damping of the longitudinal trends of slope that result from overly short or long measurement intervals.

Apart from the horizontal slice width, another aspect of the horizontal slice approach to slope measurement that can be varied is whether the slope measurements are overlapped or kept as discrete sections. Overlapping involves taking repeated horizontally sliced slope measurements at intervals shorter than the width of the horizontal slices so that adjacent slope measurements partially overlap (Figure 3.12A). In contrast, discrete horizontally sliced measurements are taken at intervals equal to the slice width so that each slope measurement is over a distinct length of channel (Figure 3.12B). Barker (2008) argued that, since the discrete approach results in a significant amount of data being discarded, the overlapping technique provides a better representation of variation in slope along the long profile of natural rivers.

Vertically sliced slope measurements involve cartographically measuring slope by finding the downstream distance necessary to complete a regular vertical drop (h). The main advantage to measuring slope in this manner is that the length over which slope is calculated varies in order to achieve the required vertical drop. This means that the physically unrealistic zero slope values associated with horizontal slope measurements are avoided. Barker (2008) found that the vertical slice approach results in greater maximum slope values than the horizontal slice approach. This is particularly the case in the headwaters of a river where the required height drop may be achieved between extremely short distances. Barker (2008) also demonstrated that in lowland reaches, excessively long downstream distances are necessary to achieve the required drop in elevation. As a result, the length over which slope measurements are assigned is extremely variable when applying the vertical slice technique (Figure 3.13).

In order to evaluate the implications of the resolution and accuracy of the various sources of elevation data and slope measurement techniques outlined above, they were each applied to several test catchments. The test applications illustrated in Figure 3.14 to Figure 3.17 refer to the Afon Einon catchment in mid-Wales, and the River Taff catchment in South Wales. These two catchments are described in more detail in Section 7.3.

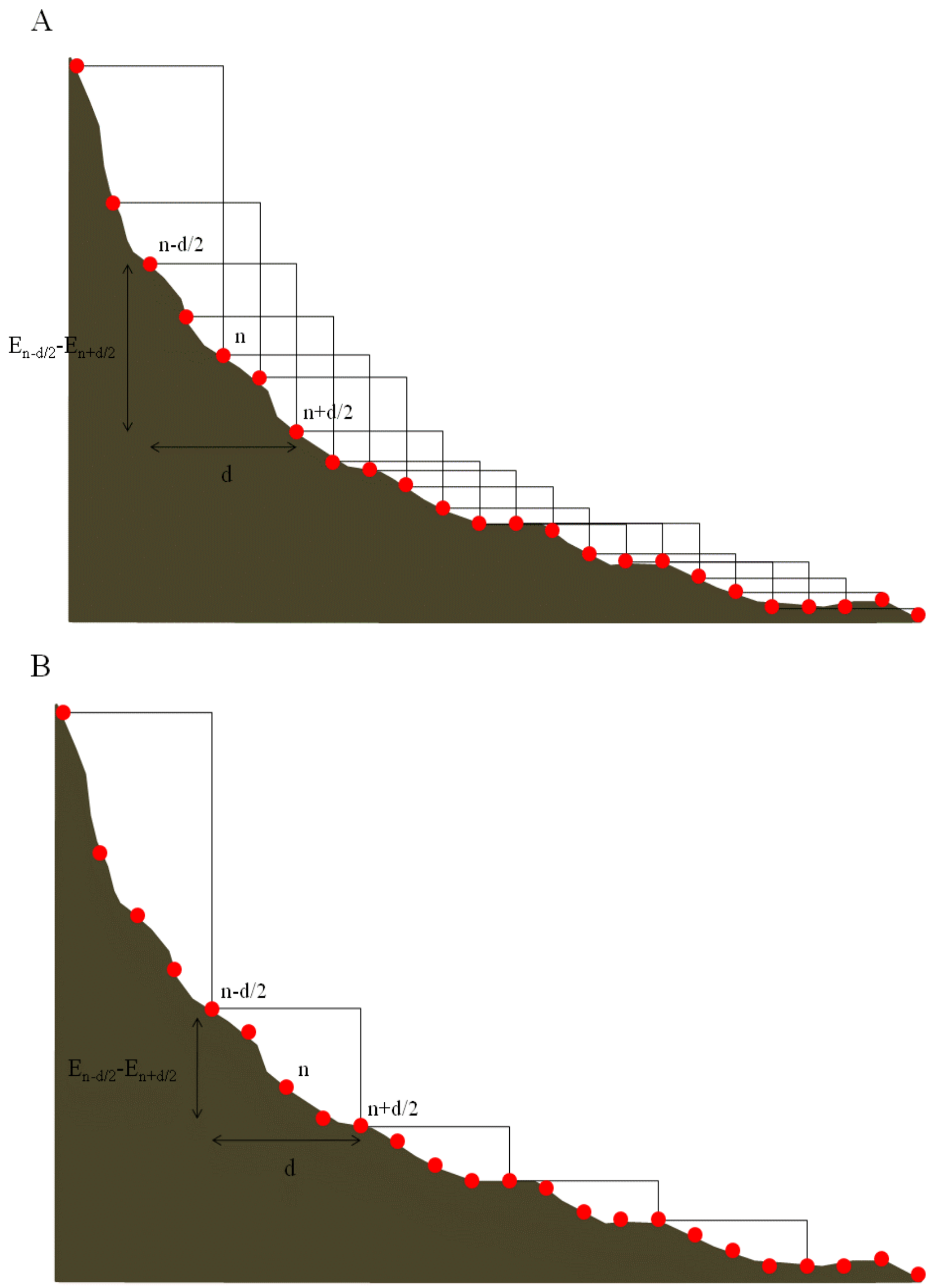

Figure 3.12 Horizontal slice measurements of slope. (A) Overlapping horizontal slices. (B) Discrete horizontal slices.

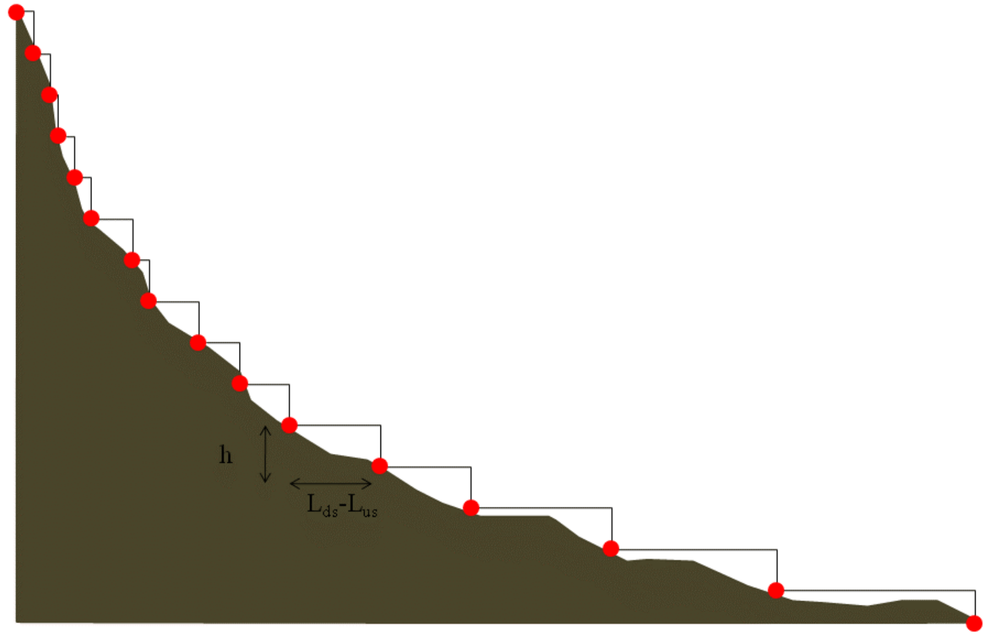

Figure 3.13 Vertical slice measurement of slope.

Figure 3.14 compares the elevation and derived slope values along the main stem of the Afon Einon when using three different elevation sources: a topographic survey using a ‘total station’; a NEXTMap IfSAR DEM; and an OS Landform Profile DEM. The topographic survey measured the elevation of the channel bed at the thalweg at 50m intervals along the main stem of the Afon Einon. For the purposes of this comparison, it is assumed that the topographic survey represents the ‘true’ elevation and slope along the Afon Einon main stem. All three data sources appear to perform similarly. However, closer examination of the OS Landform Profile elevation data reveals that it has a stepped downstream profile. This is due to it being sourced from 10-metre contour lines, which can impact on the derived slope measurements, resulting in artificial peaks and troughs that relate to the steps down and across the contours. In general, the NEXTMap elevation data appears to be far more consistent with respect to the ‘true’ elevation although, in a few places the NEXTMap and surveyed elevations diverge, resulting in discrepancies between the derived slope values.

The stepped long profile in OS Landform Profile elevation data is more evident in Figure 3.15, where it is compared with a long profile derived from LiDAR elevation data for the River Taff main stem in South Wales. The impact that this stepped profile has on derived slope measurements is also obvious here. Based on this analysis, OS Landform Profile elevation data may not, therefore, always be suitable for estimates of slope within catchment-scale assessments of coarse sediment dynamics.

Figure 3.16 compares four methods of deriving slope using the LiDAR elevation data for the River Taff main stem: i) a simple exponential model; ii) an overlapped horizontal slice approach; iii) a discrete horizontal slice approach; and iv) a vertical slice approach. The slope derived from an exponential curve fit to the elevation data ($S = 0.0324 \cdot e^{-0.00006 \cdot L}$) reproduces the general trend of declining slope through the long profile but, as discussed above and identified by others (Knighton, 1999; Harmar and Clifford, 2007; Barker, 2008), this type of slope representation does not represent local variations within basin trends which are often important to coarse sediment dynamics. As expected, the two horizontal slice approaches produce similar slope measurements, although the discrete method results in fewer unique slope values. They also both result in physically unrealistic zero slope values in several parts of the long profile. As suggested above, the vertical slice approach avoids slope values of zero and in this aspect it is preferable to the two horizontal slice approaches. However, as demonstrated by Figure 3.16, the length over which slope is measured is not equally spread throughout the basin which could cause issues with the practical application of slope values.

Figure 3.17 demonstrates the impact of varying the horizontal slice width used to measure slope on the LiDAR based long profile of the River Taff main stem. This figure supports the findings of Barker (2008) who showed that: measurements over short slice widths (50m) result in a high level of scatter; and measurements over long widths (5000m) result in dampening of longitudinal trends of slope. It is impossible to make a definite conclusion on the most appropriate slice width over which slope should be measured as it is dependent on the scale at which processes that are deemed important are acting. No means of objectively identifying the most appropriate slice width is offered here and instead expert judgement is recommended, taking into account the factors identified above.

This review of available elevation data and slope measurement is used within Section 6.6.3, where the methodology for parameterising slope within the new approach for quantitatively accounting for catchment-scale coarse sediment dynamics is described.

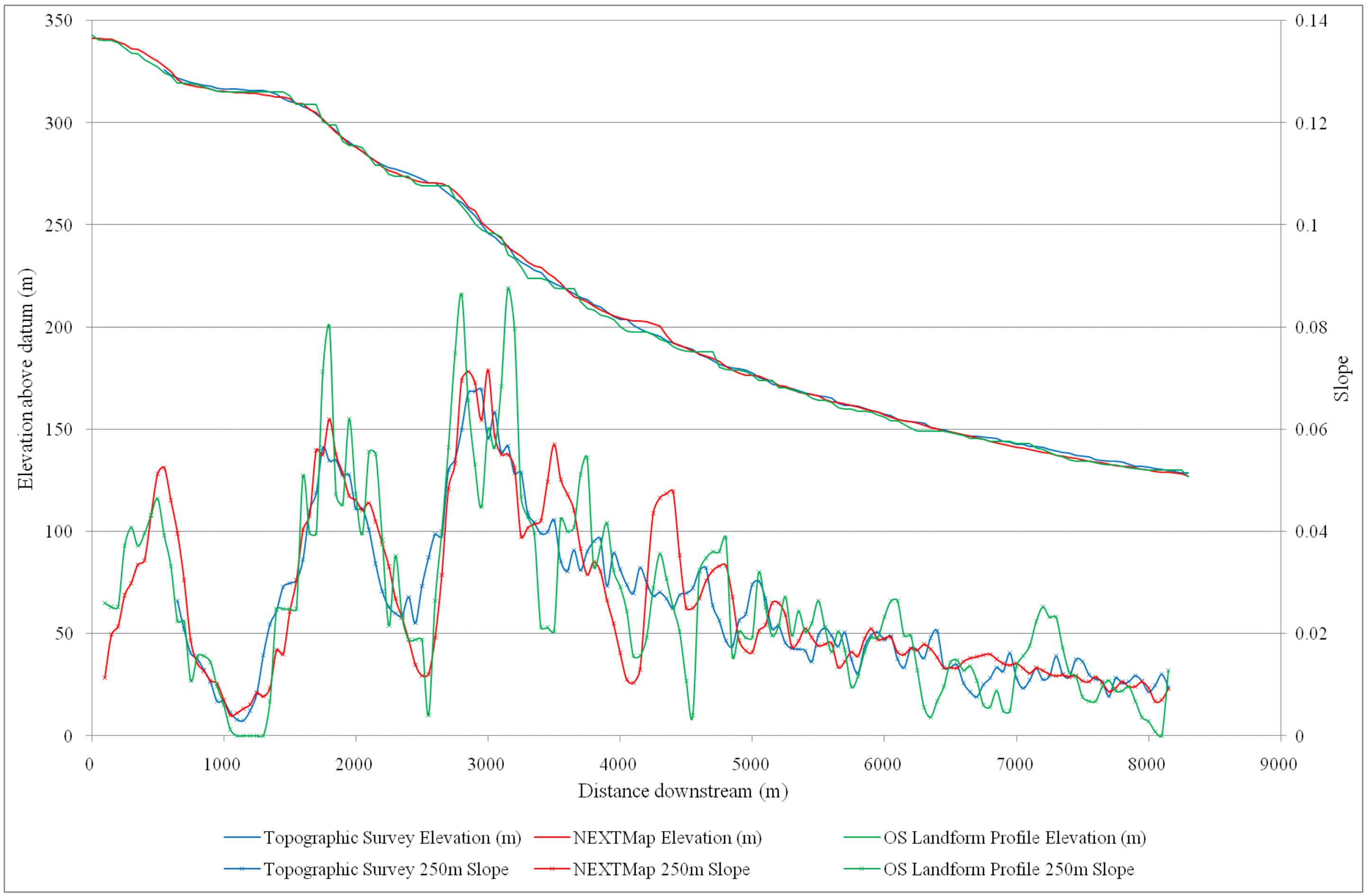

Figure 3.14 Elevation and 250m horizontal slice measurements of slope on the Afon Einon main stem long profile using different elevation sources.

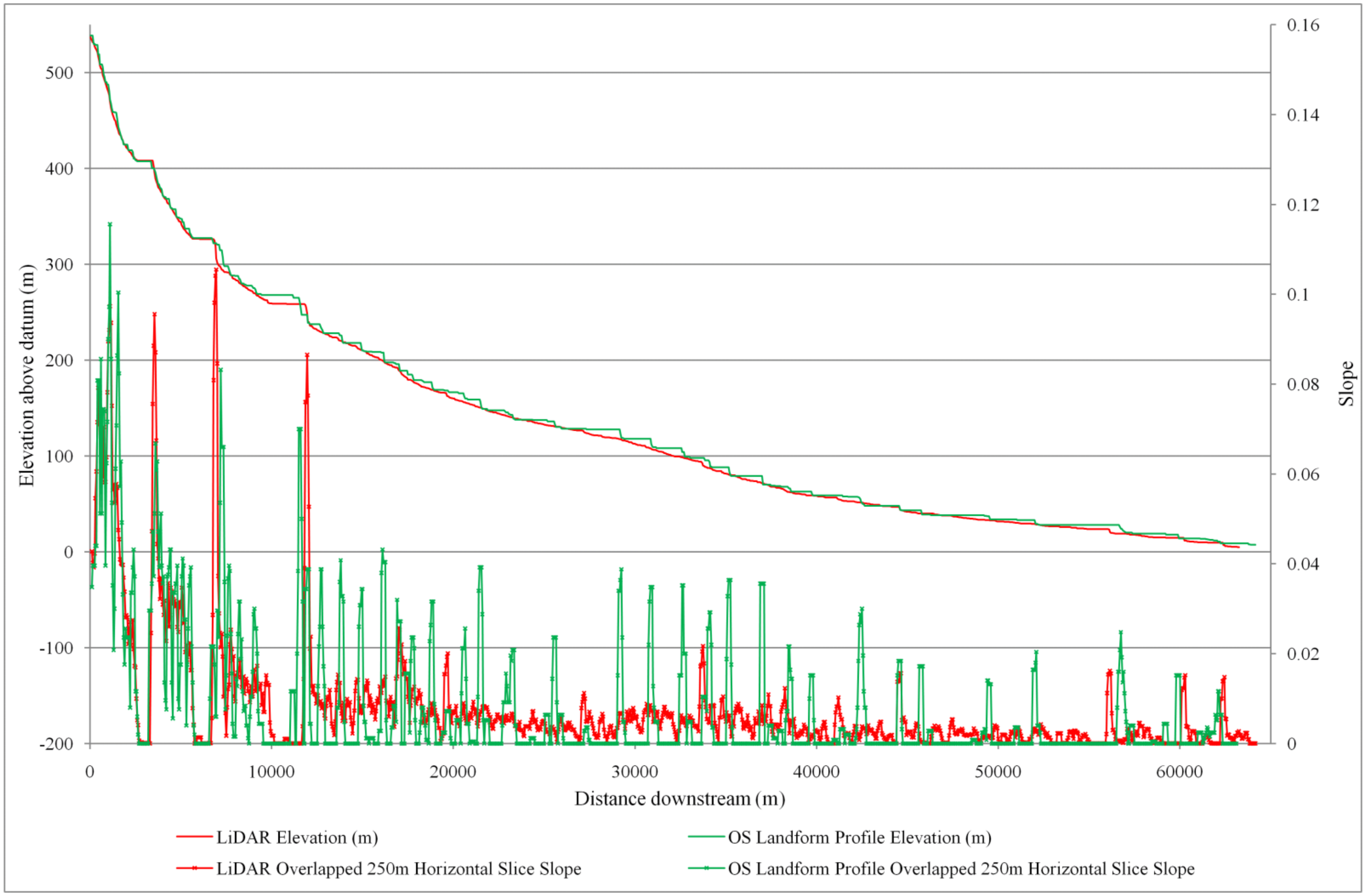

Figure 3.15 Elevation and 250m horizontal slice measurements of slope on the River Taff main stem long profile using different elevation sources.

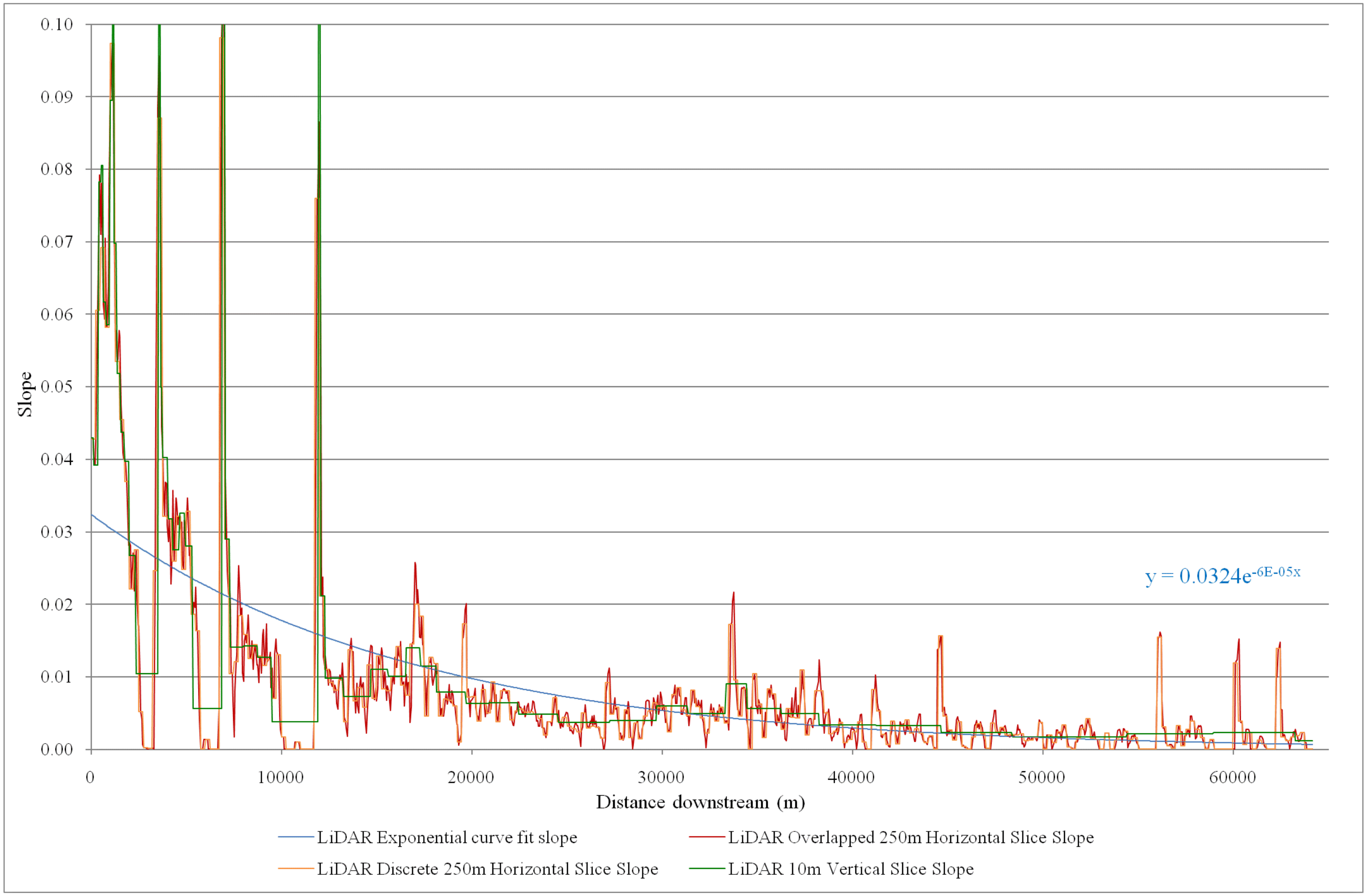

Figure 3.16 Slope measurements on the River Taff main stem long profile using a LiDAR digital elevation model and different slope measurement techniques.

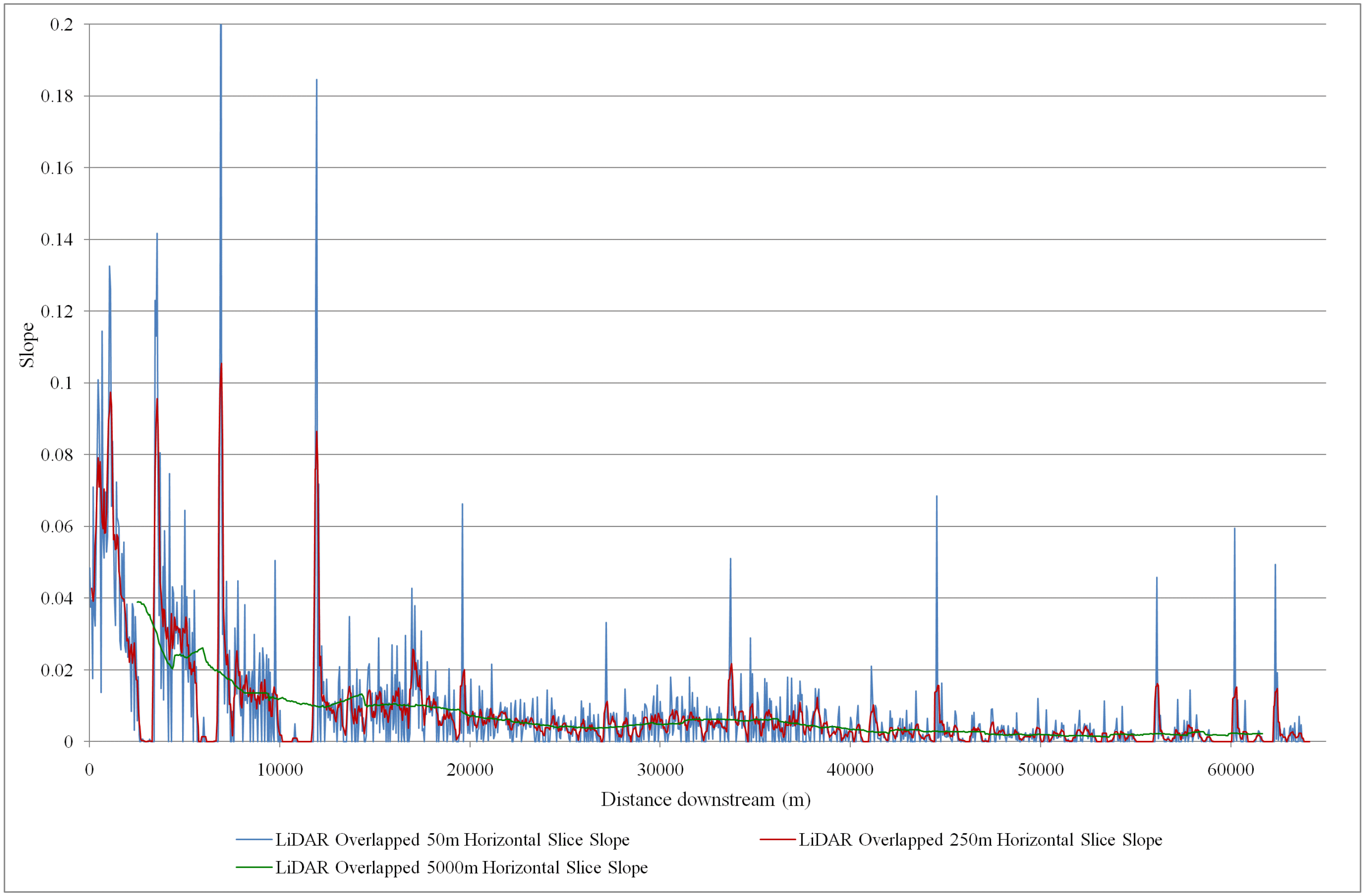

Figure 3.17 Slope measurements on the River Taff main stem long profile using a LiDAR digital elevation model, overlapped horizontal slice slope measurements and different horizontal slice widths.

3.2.4 Hydraulics: channel roughness

Bull's (1979) examination of critical stream power thresholds identified that it is not solely the erosion resistance of channel boundary sediments that affects the stream power necessary to entrain sediment, but that the hydraulic resistance of the channel also plays an important role. Hydraulic roughness controls the relationship between flow velocity and depth, and describes the balance between the downslope component of the weight of the water and the upslope resistance of the channel produced by skin friction, form drag and free surface distortion (Ferguson, 2007). A number of resistance coefficients have been developed but by far the most commonly used are the Darcy-Weisbach friction factor *'f'* and Manning's *'n'* which the ASCE (American Society for Civil Engineering) '*Task Force on Friction Factors in Open Channels'* concluded were "*probably equally effective in the solution of practical problems*" (1963: 99). The Task Force also expressed an unsubstantiated belief that roughness in open channels is best represented by the Darcy-Weisbach friction factor, although more recently Dingman and Sharma (1997) stated that the general consensus is that Manning's equation is preferable. Certainly, Manning's *'n'* has remained the most widely used flow resistance coefficient. For example, a literature review found the number of references using each equation to be: 78 for Manning, 33 for Darcy-Weisbach and 22 for alternative means (Julian Green, University of Loughborough, personal communication, 2008).

Not only are there various coefficients that can be used to represent flow resistance, there are also multiple means by which those coefficients can be calculated. Ideally, resistance coefficients like Manning's *'n'* are calculated from field measurements of flow velocity, hydraulic radius and channel slope. However, this approach to determining the flow resistance coefficient is clearly impractical in the context of this study. Therefore, it is necessary to explore other options for estimating resistance coefficients.

There are a number of methods for estimating flow resistance coefficients based on qualitative channel observations. These include: Cowan's (1956) composite representation of Manning's *'n'* based on the sum of various roughness components, including the effects of surface irregularities, shape and size of channel cross section, obstructions, vegetation and flow conditions and the meandering of the channel; Chow's (1973) tables of reference *'n'* values for specific types of channel; and Barnes's (1967) handbook of photographs depicting series of river channels of known '*n*' value. It is, therefore, possible to use information obtained from the RHS database to estimate an *'n*' value to represent the channel hydraulic roughness using any one of these methods. However, these qualitative approaches are all limited in their representation of the range of influences and complex physical processes behind overall channel roughness and use empirically derived, representative values rather than rigorous hydraulic analyses.

The limitations of qualitative estimates of channel roughness have led to the development of a new approach to estimating hydraulic roughness whereby the energy loss mechanisms, including lateral shear, transverse currents and boundary friction, are treated individually (DEFRA/EA, 2004) in a methodology termed the Conveyance Estimation System (CES). The CES represents roughness in terms of the local unit roughness 'n_1'. This n_1 value represents the roughness due to an identifiable segment of boundary friction within the channel section, rather than Manning's *'n'* which is a value applied to whole regions of the cross-section. The local unit roughness (n_1) is instead equivalent to a Manning's n that has been stripped of all the energy losses due to lateral shear, secondary flows and sinuosity. In other words, it represents the roughness caused solely by local boundary friction (bed, bank and floodplain surface material; vegetation and irregularities such as groynes, trash, pools and riffles):

$$n_1 = \sqrt{{n_{sur}}^2 + {n_{veg}}^2 + {n_{irr}}^2}$$

Equation 3.6

where 'n_{sur}', 'n_{veg}' and 'n_{irr}' are the unit roughness values due to surface material, vegetation and irregularity respectively (DEFRA/EA, 2004).

The DEFRA/EA report on the CES methodology describes how all of the remaining energy 'losses' that would contribute to total roughness / resistance (*n*) are calculated based on application of the Reynolds Averaged Navier-Stokes equations (RANS) within the conveyance estimator. These losses occur as a result of the stream-wise translational kinetic energy being transferred in part to rotational kinetic energy through the generation of vortex structures within the flow. Vortex structures may arise from various sources including: boundary friction caused by surface roughness; turbulence due to lateral shearing in regions with steep velocity gradients; transverse currents developing in regions with steep velocity gradients; water moving between the floodplain and the main channel, which is also subject to expansion losses; and abrupt changes in form in irregular channels, which cause additional 'losses'.

The CES method has been designed to be compatible with outputs from the RHS database and it therefore has the potential to be applied at the broad-scales that this study is concerned with. However, lack of detailed cross-sectional measurements within the RHS means that there are potential issues concerning the impact of uncertainty in the input data upon the channel roughness estimation (DEFRA/EA, 2004). Further, as demonstrated in Figure 3.8, despite representing an extensive national sample, the coverage of RHS sites within individual catchments is uneven and not necessarily sufficient for catchment-scale assessments of coarse sediment dynamics.

3.2.5 Channel erodibility

The erosive power of the flow is not solely responsible for driving sediment dynamics. The erodibility of the channel boundary materials also plays an important part. A study by Downs and Priestnall (1999) used GIS (Geographical Information System)-based calculations of stream power as a means of predicting channel adjustment on the River Bollin, Cheshire. They found that, at some points in the channel network, high stream power values did not generate as much erosion as would have been expected due to particularly high erosion resistance at these points. Downs and Priestnall's (1999) findings relate strongly to the theoretical arguments of Bull (1979), who described how the incidence of erosion depends not only on the available erosional power, but also on the 'critical power' for the reach in question. According to Bull (1979), critical power depends on the sediment load supplied to a reach and the erodibility of the channel boundaries. For instance, the highest stream powers found within Downs and Priestnall's (1999) study were located in a reach classed largely as morphologically inactive. Closer examination of the catchment revealed that this was due to the location of the reach within an urban centre where the channel boundaries were protected by highly resistant brick walls and culverts and, therefore, had a high 'critical power' for erosion. This example demonstrates the important influence that the erodibility of the channel boundaries has on channel adjustment and sediment dynamics and how it is "*a simplification to assume that channel change can be predicted accurately by a simple function of gross potential to do work"* (Downs and Priestnall, 1999: 261). Therefore, in accounting for sediment dynamics it is preferable to consider the factors that determine the channel's resistance to morphological change, such as the size distribution of the boundary materials and the presence of artificial protection. Unfortunately, no simple means of quantifying the erodibility of a channel in a manner similar to Downs and Priestnall's (1999) theoretical 'resisting power', or Bull's theoretical 'critical power' currently exists. It is, therefore, common to use information on the character of the material making up both the channel bed and the channel banks to infer their erodibility.

Ideally, information on boundary erodibility would take the form of a full particle size distribution because sediment entrainment and transport depend not only the median grain size, but also the particle size distribution of grains present. This results from a complex combination of size selective entrainment and relative size effects (Ashworth and Ferguson, 1988). Size selective entrainment occurs as a result of the dependence of an individual grain's mobility on its size relative to the rest of the distribution (Wilcock, 1993). The heterogeneous nature of alluvial sediment sizes further affects particle mobility as a result of bedforms, armouring and the degree of grain protrusion, that generally reduce the propensity for selective entrainment, encouraging instead equal mobility between all size fractions on the bed (Andrews, 1984; Wilcock, 1998).

A review of published bed material size data, combined with a number of samples collected by the author and other researchers at the University of Nottingham, has resulted in a national database of bed sediment particle size distributions (Figure 3.18). However, the overall paucity of measurements of bed material particle size distributions means that the national coverage provided by this database is insufficient to enable widespread catchment-scale assessment of coarse sediment dynamics across British rivers.

The RHS database includes information describing the material comprising the bed of the channel. Neither the median particle size nor the size distribution are provided, but the RHS database does give an indication of the types of sediment (clay, silt, sand, gravel, pebble, cobble and boulder) observed in the 10 spot checks, as well as recording the presence of any naturally non-erodible materials or artificial bed protection (bed rock, reinforced and culverted). Emery *et al.* (2004) used the bed sediment information in the RHS database to generate an index of sediment calibre for each site. They assigned a representative Φ size (where Φ size is the negative logarithm to the base 2 of the grain size in millimetres) to each RHS bed material class and calculated a Bed Sediment Calibre Index (SEDCAL) Φ size based on the average for the 10 spot checks:

$$\mathrm{SEDCAL} = \frac{\left((-8 \cdot BO) + (-7 \cdot CO) + (-3.5 \cdot GP) + (-1.5 \cdot SA) + (1.5 \cdot SI) + (9 \cdot CL)\right)}{(BO + CO + GP + SA + SI + CL)}$$

Equation 3.7

where BO, CO, GP, SA, SI and CL represent the number of spot checks allocated to boulder, cobble, gravel/pebble, sand, silt and clay respectively.

In order to evaluate the accuracy of this type of index derived from RHS bed material data, where an RHS site fell within 1km up or downstream of one of the sites where bed material size has been measured it has been compared with the D_{50} values from the measured bed material data in Figure 3.18.. In Figure 3.19, modal bed material Φ sizes from the RHS database and SEDCAL index Φ sizes are plotted against the median Φ sizes measured in the field. Both the SEDCAL index size, and the modal bed material size are poorly correlated with the median sizes measured at the nearby bed material sampling sites, with correlation coefficients of 0.33 and 0.50, respectively. These results indicate that RHS bed material classifications could not provide a reliable source of bed material size information for broad-scale assessment of sediment dynamics.

RHS spot checks also classify the type of bank material and the character of the riparian vegetation. This information could, in principle, be used to estimate bank erodibility. However, because of the lack of consistent national coverage of RHS sites (Figure 3.8) and concerns raised by the unreliability of RHS bed material classifications (Figure 3.19), it was concluded that the RHS database would not be a suitable source of information for representing bank material erodibility. In fact, no known data source exists for representing the erodibility of the banks of British rivers, at the catchment-scale.

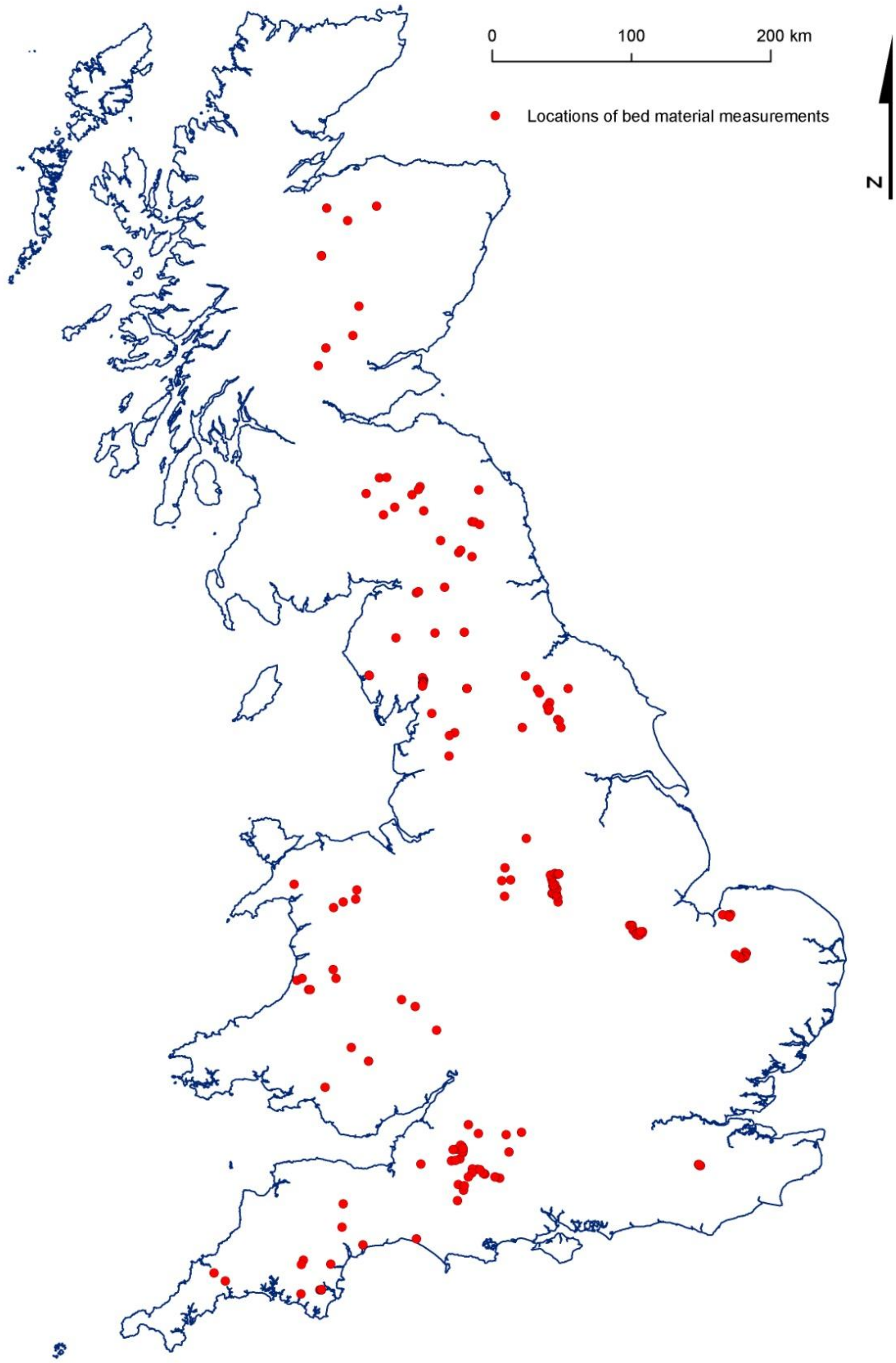

Figure 3.18 Location of known bed material size measurements within Britain.

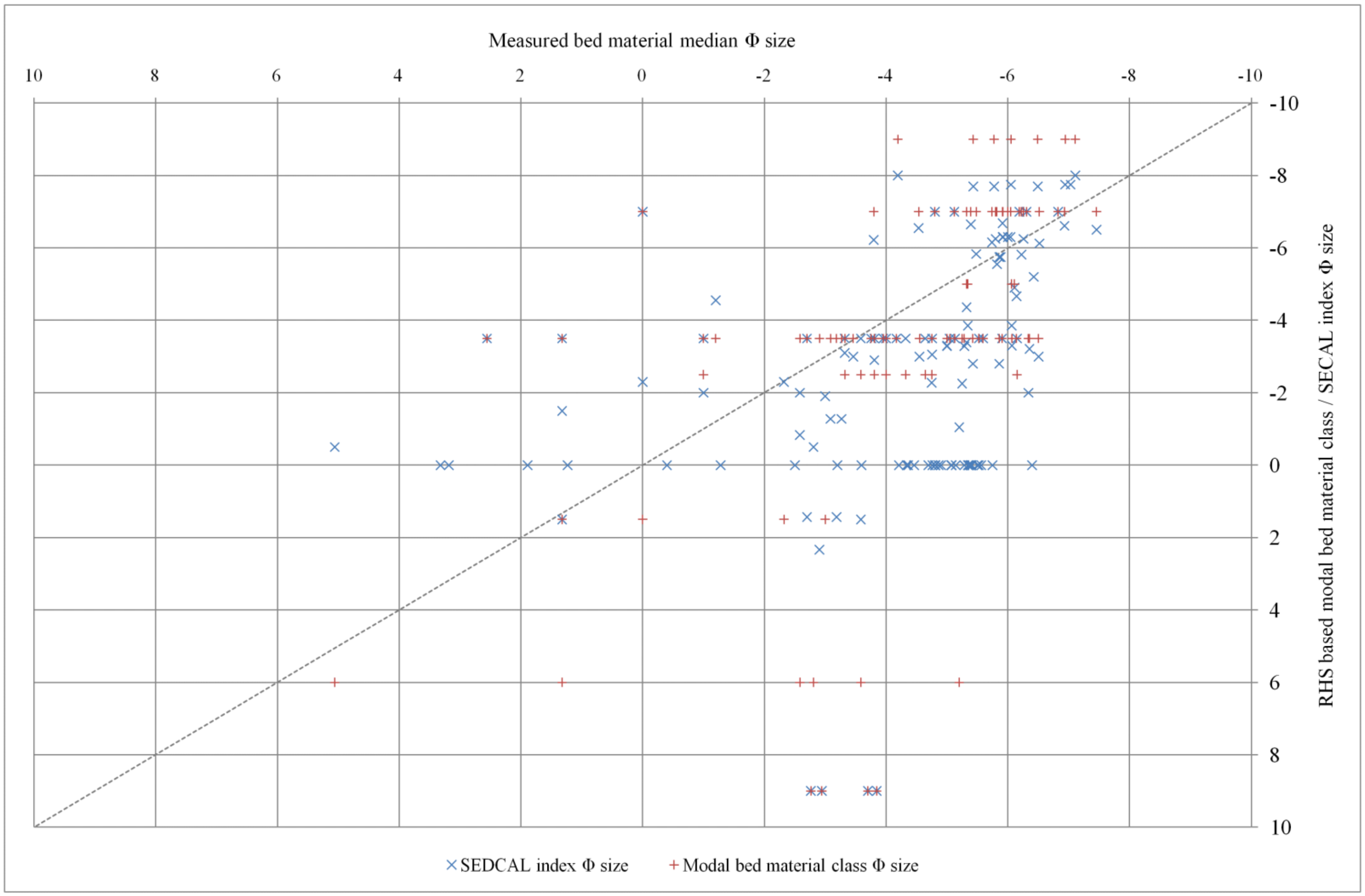

Figure 3.19 Comparison of RHS based bed material Φ size class with measured bed material median Φ size class

3.2.6 Supply of coarse material

As described by Lane (1955b) the morphology of a reach of channel is controlled not only by the flow regime and the characteristics of the channel boundary materials, but also by the sediment regime: that is the quantity, calibre and time distribution of sediment delivered to the reach. Lane *et al.* (1996) demonstrated that it is the combined effects of the flow and sediment regimes that together explain channel morphology, with discharge alone being a poor explanatory variable. Consequently, to adequately account for coarse sediment dynamics in British rivers it is essential to consider parameterisation of the supplies of coarse material from its two primary sources: (i) bed material load transport in the reach upstream; and (ii) erosion of coarse stream banks and any hill-slopes that are geomorphologically coupled to the channel, in the reach in question.

Unfortunately, the only datasets that provide measured coarse material loads in British rivers have limited spatial coverage and have periods of record no longer than 2 or 3 years as they stem from short duration research or project-related field campaigns, often performed by post-graduate students as part of doctoral studies (Leeks and Marks, 1997; Henshaw, 2009). Lack of routine monitoring results from the significant logistical difficulties and very high costs of measuring coarse material transport in the field (Gomez, 1991). Given the lack of measured data, the next best means of estimating the amount of coarse material supplied to a reach from upstream is to predict it based on the transport capacity of the reach immediately upstream. However, this approach to estimating sediment supply is complicated by the fact that the input of coarse material from the reach immediately upstream may itself be limited by the quantity of coarse material supplied to it. The difficulties encountered in predicting coarse sediment transport rates are discussed further in Section 6.2.

Church (2002) identified that, in upland regions, stream channels are directly ‘coupled’ to adjacent hill-slopes so that a range of sediment sizes, including coarse material of potential significance to broad-scale sediment dynamics is delivered to reaches running along the base of the hill-slope. These inputs locally alter hydraulics, fluvial processes, and the morphology of the reach and elevate rates of sediment supply, transport and storage in the channel network downstream (Benda and Dunne, 1997a). In a study of 21 Swiss catchments, Keinholz *et al.* (1991) estimated that 17% of coarse material was derived from the hill-slopes, with the remaining 83% coming from erosion of the channel boundaries. Schmidt (1994) recorded values of 24% from hill-slopes and 76% from channel boundaries in Bavaria, whilst Johnson and Warburton (2002) recorded similar values of 25% and 75%, respectively in streams draining the Lake District. Church (2002), described how the relative contribution of coarse sediment from hill-slopes decreases as streams transition from upland headwaters to middle-course piedmonts with wider valleys and floodplains, due to the shift from the channel being strongly coupled with its hill-slopes to being completely uncoupled. As a result, upland rivers tend to receive a high proportion of coarse sediment from hill-slope sources, while piedmont and lowland rivers with floodplains do not.

Sediment derived from hill-slope sources has been demonstrated to contribute as much as a quarter of the coarse sediment load and to influence coarse sediment dynamics throughout the fluvial system (Reid *et al.*, 2007). Unfortunately, while good information has been derived from monitoring of selected, upland, headwater streams (Harvey, 1991), there are no long term, catchment-scale datasets that provide measured data on coarse sediment delivery from hill-slopes for British rivers. Therefore, as with upstream coarse sediment supply, parameterisation of hill-slope coarse sediment supply is dependent on estimation and prediction, rather than empirical data.

The delivery of sediment from hill-slopes to rivers is critically dependent upon: the rate of erosion and/or failure of the slopes themselves and; the efficiency with which hill-slope sediment sources are connected to the channel and drainage network (Brunsden and Thornes, 1979). There has recently been significant progress in the application of slope stability models at the catchment-scale due to growing availability of high-resolution topographic data, improvements in computational aspects of data handling, and the associated development in modelling capabilities. Much of this progress has been based upon catchment-scale application of infinite-plane slope models, often in a GIS framework, to determine the conditions at which failure would occur (Reid *et al.*, 2007). For example, SHALSTAB is a model that calculates the ratio of effective precipitation to soil transmissivity (Q/T) to assign relative landslide hazard across a landscape. This provides a relative probability of failure for all areas in the landscape. However, it requires a user defined, critical Q/T value to predict where failures will actually occur and, consequently, its ability to predict sediment delivery volumes without additional data is limited.

The efficiency of channel to hill-slope coupling governs the transfer of sediment from hill-slope sources to the channel. Transfer efficiency is therefore dependent on the proximity of the source to the channel network, and the capacity of gravitational and fluvially driven earth surface processes to carry the sediment to the stream. For example, if a landslide runs out into a river channel, coupling is strong and the source delivers much of the sediment involved in the slope failure directly to the fluvial system. Conversely, the same landslide on a hill-slope that is remote from a channel would have low degree of connectivity, so that little of the liberated sediment would enter the drainage network. In upland systems, where the channel sides are steep and valley floors are narrow, coupling tends to be strong, with sediment readily supplied to steep, often bedrock, channels (Stelczer, 1981). In lowland systems, where the slopes are gentle and valley floors are wide, coupling between hill-slopes and the channel can be weak or non-existent and little hill-slope derived material enters the drainage network (Hooke, 2003). Reid *et al.* (2007) describe a new method for better identifying coarse sediment delivery from hill-slopes to channels. This is based on the concept that coarse sediment from hill-slopes can only be transferred to the channel if it is sources from an area that is hydrologically linked to the channel. However, despite progress in modelling hill-slope-channel connectivity further testing and calibration is required before it will be possible to make routine predictions of sediment delivery from hill-slope processes at the catchment-scale.

3.2.7 A summary of available data appropriate for widespread catchment-scale modelling of coarse sediment dynamics in British rivers

It is apparent that it is not currently possible to parameterise all of the factors that affect coarse sediment dynamics. No dataset that provides full representation of channel cross-section geometry is available, and while the RHS database can provide estimates of channel size and shape, it too is limited in terms of national coverage. Similarly, there is a paucity of data describing channel boundary materials in British rivers and, again, while the RHS database can provide estimates of reach-averaged bed material class, these estimates have proved unreliable when tested against measured particle size distributions. Clearly, these data limitations are bound to have an impact on the ability of any approach to account for coarse sediment dynamics in British rivers. Table 3.2 summarises the findings of the preceding sections in terms of the appropriateness of the data currently available. It is evident that the only factors that can currently be parameterised adequately at the catchment-scale are: hydrology (in the form of synthetic FDCs generated using a method similar to Low Flows 2000; channel widths extracted from OS MasterMap data; and channel slopes calculated from high resolution digital elevation models like IfSAR and LiDAR. These findings significantly limit the approaches that could be applied when accounting for catchment-scale coarse sediment dynamics in British rivers. The specific methodology for parameterising these factors will be finalised once the approach for accounting for catchment-scale coarse sediment dynamics has been developed (and is described in Section 6.6).

Table 3.2 Summary of available data appropriate for widespread catchment-scale modelling of coarse sediment dynamics in British rivers

Factor of interest	Data available	Suitability	Coverage
Hydrology	- National River Flow Archive	Very good	Limited to gauging stations
	- *Prediction of FDCs within ungauged catchments using drainage area, rainfall, potential evaporation and soil hydrology data*	*Reasonable approximation*	*Continuous national coverage*
Hydraulics: Cross-section geometry	- 'Section 105' surveys	Very good	Poor
	- Hydraulic geometry relationships	Fails to account for potentially important local variations	Continuous national coverage
	- River Habitat Survey (RHS)	Reasonable approximation	National but inconsistent coverage
	- *Ordnance Survey MasterMap widths*	*Good, but widths only*	*Continuous national coverage*
Hydraulics: Slope	- *Digital Elevation Models (LiDAR, IfSAR, OS Landform Profile)*	*Variable (LiDAR and IfSAR good)*	*Coverage of the majority of significant watercourses*
Hydraulics: Channel roughness	- RHS using the Conveyance Estimation System	Reasonable approximation	National but inconsistent coverage
Erodibility of channel	- Measured bed material data	Good	Poor
	- Bed and bank material classification from the RHS	Poor approximation	National but inconsistent coverage
Supply of coarse material	- None	-	-

3.3 Critique of existing approaches for assessing coarse sediment dynamics

3.3.1 Introduction

During the late twentieth century, the emerging need to consider sediment at the catchment-scale identified in Section 2.4 triggered research and development of approaches to represent catchment-scale sediment dynamics in a number of countries, leading to Australia's SedNet scheme (Prosser *et al.*, 2001) and the USA's system of Regional Sediment Management (Rosati *et al.*, 2001). However, lower sediment loads and a history of well-organised river management associated with British rivers meant that, until recently, there has been limited need to consider coarse sediment dynamics at the catchment-scale. However, the need to account for sediment in British rivers has recently become more pressing due to increasing environmental awareness by policy makers and increased pressures on fluvial systems and their ecosystems. Yet, despite this pressing need, the tools currently available for addressing sediment dynamics in British rivers may be unsuitable for application across entire catchments. This section examines the utility of existing sediment analysis tools in accounting for catchment-scale, coarse sediment dynamics.

3.3.2 Fluvial Audit

At present in the UK, the primary means by which routine assessments of sediment-related problems within a catchment context can be performed is through using the qualitative Fluvial Audit (Sear *et al.*, 2003). This approach attempts to relate sediment movement, channel stability and morphological change at the reach-scale to sediment dynamics in the surrounding fluvial system and wider catchment. In practice, a field and documentary investigation is used to divide the fluvial system into geomorphic reaches designated as: source, transfer, exchange, or sink reaches. The approach involves detailed field reconnaissance of the watercourse performed by an experienced fluvial geomorphologist (Thorne, 1998). Examples of its successful application include a geomorphological evaluation of the Missouri River in Montana following the construction of Fort Peck Dam. Claims from local landowners that the dam's construction had instigated instability in the river channel, threatening agricultural development, were shown to be false. In fact, the Fluvial Audit indicated that bed degradation and bank erosion had declined, with the channel approaching dynamic equilibrium (Darby and Thorne, 2000).

However, whilst the Fluvial Audit approach has proven very useful in studying river management issues (exemplified by the Missouri River example above), along with river conservation and restoration projects, it does not support the quantification of sediment dynamics required to interface effectively with the contemporary engineering components of strategic flood studies and Catchment Flood Management Plans (Thorne *et al.*, 2006). Therefore, whilst the Fluvial Audit approach may provide useful insights into catchment sediment dynamics, it is of limited utility for strategic planning due to its heavy dependence on expert observation, interpretation on the part of the auditer and its lack of quantitative outputs. Further, the extended input by experienced geomorphologists required by the approach limit its application to project-related studies with obvious sediment issues and the substantial resources necessary to support field and archive investigations (Thorne *et al.*, 2006).

3.3.3 Physically-based mobile bed 1-D hydrodynamic models

Theoretically, system-scale sediment dynamics can be quantified using mobile bed versions of established 1-D hydrodynamic models such as HEC-RAS (Brunner, 2006) and ISIS (ISIS, 1999) that have a sediment transport module. These models were originally designed for flood routing to predict the water levels associated with the passage of a flood wave moving through a fluvial system. They work by solving the St. Venent equations for gradually varied, unsteady flow to predict flow velocities and depths based on a given flood hydrograph, and a series of regular channel/floodplain cross-sections. Mobile bed modules have since been attached to these 1-D hydraulic models to predict sediment transfer, along with channel morphological adjustment. Simulation of sediment transport and bed level changes in these models is based on calculation of sediment transport rates at each computational node. A number of different sediment transport formulae can be specified in the models, with the ability to calculate transport by size fraction. The explanatory variables for the sediment transport calculations are derived from the sectional hydraulic properties calculated within the hydrodynamic computations. A key feature of these models is that the effects of erosion or deposition are represented after each iteration by updating the cross-sectional geometries based on the difference between sediment transported in and out of reaches between the cross-sections. The amount of bed level change is found from the balance of sediment entering and leaving the reach: a simple mass balance computation performed using the Exner equation:

$$(1-\lambda)\cdot W\cdot\frac{\delta z}{\delta t}+\frac{\delta Q_s}{\delta x}=0$$

Equation 3.8

where λ is bed porosity; W is water surface width (m); z is bed elevation (m); t is time (s); Q_s is sediment transport rate (m^3s^{-1}); and x is distance in flow direction (m).

The range of applications of 1-D sediment models in the UK or by UK-based consultants is progressively increasing, and is illustrated by the list of known recent applications of ISIS Sediment compiled by Green (2006). These range from flood defence design studies to research and post-flood event investigations, but are generally limited in scale to investigations of particular project reaches, rather than catchment-scale modelling. For example, Walker (2001) demonstrated the implementation of ISIS Sediment on the River Eden in Cumbria in an attempt to determine the geomorphological impacts resulting from the construction of a weir. Within this application, Walker (2001) demonstrated the utility of sediment transport modelling and post-project investigations confirmed that the findings of the modelling exercise were fundamentally correct.

Application of mobile boundary modules within 1-D hydraulic models like ISIS and HEC-RAS is, however, highly data and time intensive. For mobile-bed applications, these models require closely spaced and detailed channel cross-sections, bed material particle size distributions and reliable estimates of channel roughness. Unfortunately, as established in Section 3.2, these data are not widely available for British rivers. Therefore, despite their proven value for investigating local and reach-scale sediment transport and sediment-related channel instability problems and their utility in exploring project-specific management options, these models are prohibitive to apply in terms of run times, data acquisition and personnel costs at the scale of a whole catchment. This limits their usage to project-related studies of reach-scale scour/fill issues rather than catchment-scale investigation of sediment dynamics and morphological responses to imbalances in the sediment transfer system.

Further, fully unsteady flow numerical models suffer from issues associated with convergence, consistency and stability (Versteeg and Malalasekera, 1995). It therefore requires many years of experience and a thorough knowledge of open channel hydrodynamics to finesse model solutions when these models are applied to watercourses that possess the degree of natural variability displayed by British rivers. On top of this, the ability of the sediment modules these models use is limited by the accuracy of the sediment transport equations within them – rendering sediment predictions no more than 'indicative' in most applications. These factors limit the application of these models to the small minority of project-related studies with resources sufficient to justify detailed data collection and the employment of specialised sediment transport modellers.

A number of mobile boundary 1-D hydraulic models have been developed specifically to model coarse sediment transport. One example is SEDROUT (Hoey and Ferguson, 1994) which was recently used to investigate the potential response of the St. Lawrence River, Quebec to short-term climate change (Verhaar *et al.*, 2008). In a manner similar to HEC-RAS and ISIS, SEDROUT solves depth-averaged flow equations using a step-backwater method and a choice of friction equations; uses the calculated shear stresses at each cross section to compute bed-material transport using a choice of sediment transport equations; then updates bed level and composition using the Exner and Hirano equations for overall and fractional sediment conservation, respectively.

SEDROUT was first applied to simulate rapid downstream fining of bed material by size-selective transport in a small gravel-bed river (Hoey and Ferguson, 1994) but it has subsequently been shown to have applicability across a range of time- and space-scales (Hoey *et al.*, 2003). For example, SEDROUT has proved capable of reproducing the sediment impacts and morphological response of artificial straightening of a meandering, gravel-bed river in Québec (Talbot and Lapointe, 2002), changes in sediment flux and bed composition along a large gravel/sand tributary of Fraser River, Canada (Ferguson *et al.*, 2001) and changes in morphology of tributaries to the St. Lawrence River over a 100-year period in response to short-term climate changes. However, like ISIS and HEC-RAS, application of SEDROUT requires data inputs that are not widely available for British rivers. For example, in order to run SEDROUT on the tributaries of the St. Lawrence river Verhaar *et al.* (2008) collected continuous bed topography data from a boat using sonar and GPS and derived bed material size from samples collected at closely spaced cross-sections. As identified in Table 3.2, these parameters and this level of coverage are not generally available for British rivers and, therefore, application of models like SEDROUT is limited to specific reaches of interest to research or river management projects.

Within many aspects of river science, it is common practice to divide the drainage network into segments, usually termed reaches, of channel that are internally relatively homogenous in nature, and comparatively discrete. This simplifies the complex hierarchy of channel forms and processes, making the fluvial system more manageable for both research and management purposes. A number of existing catchment sediment models are based on reach-based analyses, including: the Riverine Accounting and Transport model (RAT - Graf, 1994; Graf, 1996); the Sediment Impact Assessment Model (SIAM - Biedenharn *et al.*, 2006b; Gibson and Little, 2006), and the River Energy Audit Scheme (REAS - Wallerstein *et al.*, 2006). SIAM and REAS are reach-based, sediment balance models that are examined in Section 3.3.5, whilst RAT is a physically-based, mobile boundary model that is, theoretically, similar to the mobile boundary versions of ISIS and HEC-RAS, but with a reduced spatial complexity. It routes water and sediment through the river system, accounting for inputs, transport, internal storage and outputs. Where it differs from the approaches described previously in this section is that, rather than attempting to represent channel geometry with a quasi-continuous grid of channel cross-sections, it divides the river system into a series of discrete channel reaches with rectangular geometries. Each reach is represented by reach-averaged values of width, depth and gradient. As a result, it uses a much simpler spatial representation of the fluvial system than approaches like ISIS and HEC-RAS. Nevertheless, like ISIS and HEC-RAS, it is process-based, iterative, self-updating, and spatially variable. The basis for model operation is repeated calculation of the hydraulic characteristics of open channel flow through solution of equations for continuity and mean velocity (using Manning's equation) combined with boundary conditions that define the initial channel geometry and roughness. Sediment transport capacity is then calculated using Bagnold's (1966) sediment-transport functions, with input depths produced by the hydraulic calculations. The model iteratively calculates the movement of sediment through the system for simulated time steps, updating the initial boundary conditions to account for erosion and sedimentation before beginning the calculations for the next time step.

Thanks to its reach-based, spatial simplification, RAT requires significantly less parameterisation than models based on closely spaced cross-sectional nodes. Rather than attempting to work with a quasi-continuous representation of channel geometry, slope, bed material size and roughness, RAT simply deals with mean values of width, depth, channel roughness, bed sediment size and gradient for each reach. This means that reach-based models like RAT are far simpler to develop and running them does not demand excessive computational power. As a result, RAT is much easier to apply at the catchment-scale than the mobile boundary versions of 1-D hydrodynamic models. However, despite their relative simplicity, models like RAT are still dependent on data inputs which, based on the analysis in Section 3.2, are currently unavailable for British rivers.

Therefore, in order for RAT to be employed as part of investigations to support a British river management project, significant investment into data collection would first be necessary.

Aside from the difficulties in obtaining the data necessary to run them, an important criticism of mobile boundary 1-D hydraulic models is that, despite their complex nature, they under-represent the dimensions and styles of channel adjustment observed in nature. Adjustments of flow hydraulics and channel morphology towards dynamic equilibrium with the flow regime and supply of sediment from upstream and local sources involve simultaneous adjustments to a large number of dependent variables, many of which are mutually interactive. In this context, Hey (1988) defined the nine degrees of freedom of channel adjustment, with the partitioning of channel cross-section adjustment into its width and depth dimensions just one of several divisions of adjustment type. Hey's framework recognises the possibility of channels adjusting predominantly through lateral or vertical changes, depending on the nature of the disturbance, to a pre-existing, dynamically-stable condition. For example, in a study of the evolution of the Toutle River system following its disturbance by the eruption of Mount St. Helens, Simon and Thorne (1996) demonstrated that, since only the very highest flows were able to erode the channel bed materials, channel widening through bank erosion constituted the dominant process-response mechanism. Such circumstances, render conventional 1-D, mobile bed models such as ISIS and HEC-RAS inapplicable because they assume that imbalance in sediment continuity between adjacent computational nodes must be satisfied solely by changes in bed elevation. As demonstrated by Thorne and Osman (1988), morphological models that ignore other potential dimensions of adjustment, such as widening through the collapse and rapid retreat of the banks, cannot hope to reproduce the observed behaviour of unstable streams with weakly cohesive bank materials that limited the degree of incision to less than the critical bank height for mass instability.

A final limitation of mobile bed models is their dependence on sediment transport equations. Whilst a large number of equations for sediment transport have been developed, because each transport equation is developed for specific conditions employing different equations for similar conditions will yield transport rates that can differ by orders of magnitude (Simons and Senturk, 1992). In general, sediment transport equations are only able to predict sediment load to within +/- 50% about 60% of the time (Yang *et al.*, 1996). Therefore, when using the sediment transport equations for a particular case, special care must be taken to select equations that have been developed under conditions similar to those in the stream in question. Simons and Senturk (1992) suggest that, ideally, sediment transport formulae should be refined and calibrated for particular applications using site-specific field data. Selecting an appropriate sediment transport equation is crucial to producing a successful simulation, yet there are no universally accepted rules concerning which equation is suitable for a particular river environment. Therefore, in addition to the issues discussed above, the fine detail required to calibrate sediment transport formulae within individual reaches makes catchment-scale assessment of coarse sediment dynamics using existing 1-D, mobile bed models less attractive than might they might appear on first examination.

3.3.4 Reduced complexity cellular models

The difficulties of applying process-based, hydrodynamic models to natural rivers with complex morphologies at anything except the reach-scale and over any period of continuous simulation longer than a few months or years have, over the last decade, led to the development of several ‘reduced complexity’, cellular models designed to solve these scale-related limitations (Coulthard *et al.*, 2007). As touched upon in Section 2.5.10, cellular models represent the modelled landscape with a grid of cells, with morphological evolution of the topography being determined by the fluxes of water and sediment between cells. These fluxes are predicted using rules based on simplifications of the governing physical processes (Nicholas, 2005). In fluvial geomorphology, cellular models use simplified or ‘relaxed’ versions of the complex equations describing the flow of a Newtonian fluid used in traditional, 1-D hydrodynamic or hydraulic models. This allows a substantial increase in speed of operation, which in turn, enables them to be applied to long reaches and large catchments over time-scales useful for management purposes. Importantly, the increase in computational speed and simplicity also allows these models to simulate sediment transport between cells based on representations of the physical processes responsible that are more complete, meaning that morphological changes can be modelled over large areas and long timespans.

The first of these cellular models was the braided river model of Murray and Paola (1994). This simulated the morphological development of a braided river by routing water discharge through a grid of cells representing the topography of the channel and braid plain based on local variations in bed slope. The spatial distribution of erosion within these cells was simulated according to simple discharge-dependent erosion rules, with the eroded material being transported to adjacent cells again according to local bed slope. Their simple flow model allowed divergent and convergent flow and, importantly, the width of channels was represented by one or more cells. Despite a lack of calculations for local depth, momentum or velocity, Murray and Paola's (1994) model produced braided patterns that were at least qualitatively realistic. Importantly, it also reproduced the downstream and lateral migration of bars and sub-channels characteristic of the dynamic behaviour of braided rivers. The importance of this model was that it demonstrated that by simplifying the representation of physical processes, it was possible to recreate the patterns of behaviour observed in rivers with laterally unconstrained flow, mobile bed materials and erodible banks – performance that no conventional, hydrodynamic model could match. This simple model represented a paradigm shift in both visualisation and modelling: indicating that it is not always necessary to pursue reductionist approaches, simulating all the physical processes operating within a river channel faithfully, when modelling morphological adjustment and evolution in unstable, alluvial rivers.

As a result of this 'paradigm shift', a number of new, more advanced cellular models have been developed. For example, Coulthard *et al.* (1998) developed a cellular automaton model of river catchment evolution that was further developed into the CAESAR model (Coulthard *et al.*, 2005). This model built upon the flow routing methodology developed by Murray and Paola (1994) by including a calculation of flow depth, a more detailed representation of sediment transport using multiple grain sizes, and adding hill-slope processes (e.g. land-sliding and soil creep). CAESAR has been applied to a range of river catchments and reaches (4 to 40 km^2) with grid cell sizes ranging from 2m by 2m to 50m by 50m. Additionally, Thomas and Nicholas (2002) developed a cellular model of braided rivers (termed CRS) that used a flow model refined from the Murray and Paola method. They applied this to a 470 by 230 m reach of the Aroca River, New Zealand with 1m grid cells, producing inundation extents and flow velocities that compared favourably to results of a 2-D, CFD model of the same reach.

Nicholas (2005) commented that these types of cellular models represent one of the most important advances in fluvial geomorphology during the last decade. The basis for this statement is that cellular modelling offers the potential to simulate morphological change in river catchments and reaches over time and space-scales that are pertinent to anthropological interests (e.g. 1–100 years and 1–100 km^2). However, despite its obvious potential, the fundamental methodologies applied in this branch of modelling are still under development, and the philosophical justification for their simplification of physical processes remains the topic of debate. For example, only recently have cellular models attempted to replicate natural river meandering forms (Coulthard and Van de Wiel, 2006a) and then with only limited success. Whilst the lateral erosion algorithm within CAESAR has been demonstrated as being able to replicate the morphological migration of meander bends, it is based on the local planform curvature and, therefore, uses a symptom of lateral erosion to drive it, rather than the real cause (secondary flow circulation and elevated near-bank velocities). This example not only demonstrates the emergent stage of development that cellular models are currently in, but also the philosophical difficulties involved in modelling physical processes in a non-reductionist manner. Further, because reduced complexity models are fabricating representations of Newtonian physics, rather than being based on first principles, they are dependent on somewhat empirically derived calibration values to control the quantities of form and rates of process. These calibration coefficients can be set to values that ensure cellular models produce outputs that replicate those observed historically (hind-casting), but in predicting future conditions (forecasting) they can only produce 'best guesses' based on the expert insight and judgement of the modeller. Concerns over the extent to which the type of pattern recreation attempted by reduced-complexity models actually represents physical processes are described in detail by Brasington and Richards (2007).

A further limitation on the application of cellular models to assess catchment-scale, coarse sediment dynamics in British rivers is the data required to run them. Coulthard and Van de Wiel (2006b) describe the data requirements of CAESAR as being: hourly rainfall data for the catchment; a digital elevation model covering the entire catchment; and, crucially, the sediment size distribution for every cell in the model. As identified in Section 3.2.5, there is a paucity of information available on the sizes of bed and bank material in British river *channels*, let alone for elsewhere in British river *catchments*.

Finally, despite their reduced complexity, application of cellular models to large catchments is still currently hindered by contemporary computing power. Two issues are responsible for this computational limitation to the duration, area of application and resolution of cellular models (Coulthard *et al.*, 2007). First, when routing unsteady flows of water and sediment across a model domain, the model can only operate at rates below the rate of water and sediment movement. Secondly, restrictions on computational stability prevent changes in the elevation of a cell that are larger than a fraction of the difference between its elevation and that of the adjacent cells, limiting the amount sediment moved in any one time step. As a result, there is a limit to the number of cells that can be represented within a single model, meaning that catchments larger than ~100km^2 can only be represented using grid sizes larger than 10m (Coulthard *et al.*, 2007). Therefore, there remains a trade-off between the size of the catchment being modelled and the detail with which the channel is represented.

In summary, currently at least, cellular models should not be used for prediction of catchment-scale, coarse sediment dynamics. At present, their primary application is in the exploration of histories and possible futures of morphological change. As with the insights gained from Murray and Paola's (1994) work on braided river systems, by modelling forms rather than processes operating in complex physical landscapes, reduced complexity models can help us understand more about how they evolve. In fact, Brasington and Richards (2007) conclude their review of reduced complexity models by suggesting that, despite their limitations, it is likely that they will always have a place in geomorphology as an exploratory tool for the study of morphological change, especially where they generate observable properties of morphological dynamics and where there is value in focusing on intermediate scales that might otherwise be neglected. Following necessary further development, future versions of CAESAR or CRS should help the next generation of geomorphologists to understand how fluvial systems behave at the catchment-scale.

3.3.5 Reach-based sediment balance models

The concept underpinning reach-based sediment balance approaches springs from sediment continuity principles first proposed by Exner (1925), whose equation describes the conservation of sediment mass in a fluvial system (Equation 3.8). In its most commonly-used form, it uses the principle that mass can neither be created nor destroyed to define how the amount of sediment stored in the bed changes in response to a net difference between the incoming and outgoing rates of sediment transport. This principle is the justification for the reach balance approach as a means of predicting, on the basis of the difference between sediment supply and local transport capacity, whether a given reach has the potential to gain or lose sediment during a specified period. The total mass of sediment that any specified channel reach can transport annually can be calculated by integrating its annualised flow duration curve with its sediment rating curve. It has been argued that the balance or imbalance between the annualised sediment transport capacities in successive reaches can indicate whether the downstream reach is likely to be dynamically stable or in a state of disequilibrium. In disequilibrium situations, the direction and degree of sediment imbalance indicates the capacity for the flow to do geomorphological work on the river channel through erosion or deposition-led adjustments that drive morphological change (Phillip Soar, University of Portsmouth, personal communication[1], 2009).

Equilibrium and disequilibrium are contested terms within geomorphology, with confusion deriving from inconsistent usage across spatial and temporal scales. This confusion relates to geomorphological approaches coming from one of the two contrasting geomorphological approaches to the understanding of landforms described in Section 2.5: the *functional* and the *evolutionary/historical*. Clearly, a geomorphologist's opinion of whether a particular reach is in equilibrium depends on where their perspective falls between the functional and evolutionary approaches and, therefore, on the temporal and spatial scales they are interested in. Consideration of the impact that scale has on the perspective from which geomorphological features are examined was pioneered by Schumm and Lichty (1965) and others have subsequently taken their idea of causality being scale-dependent and applied it to multiple aspects of geomorphological study, including the notion of equilibrium (Howard, 1988). Reach slope can therefore be considered to be in various forms of equilibrium over a range of time-scales. Over *static time* (typically hours to months), flow intensity may be below the threshold level for entrainment of bed material, so no change is apparent in an equilibrium reach's slope and it can be described as being in *static equilibrium* (Figure 3.20A). Over the longer *steady time* scale (typically years to decades), with which the functionalist approach to geomorphology was concerned, significant but temporary departures from the equilibrium slope occur in response to excessive erosion and/or deposition of bed material associated with individual, high magnitude sediment transporting events. However, subsequent redistribution of sediment during periods of low to moderate discharge leads to recovery of the reach's equilibrium slope. Hence, over annual to decadal periods reach slope

[1] Soar, P., Wallerstein, N. P. In review. Characterising sediment transfer in river channels using stream power. River Research and Applications.

fluctuates around an equilibrium value as erosion and deposition are balanced. At this time-scale, the reach can be described as being in *steady-state equilibrium* (Figure 3.20B). Over the far longer, *dynamic time* scale (typically thousands of years), an equilibrium reach experiences countless high flow events and a slight imbalance between the sediment eroded and deposited in the reach during each of these events will lead to a progressive change in slope at this temporal scale. If the factors controlling the imbalance in erosion and deposition remain relatively constant through time then this change will occur at a consistent rate and the reach will be in *dynamic equilibrium* (Figure 3.20C). Finally, over a *cyclic time* scale (typically millions of years), with which the evolutionary approach to geography was concerned, progressive decreases in an equilibrium reach's slope will cause the relative imbalance in erosion and deposition in the reach to decrease over time and it is in a state described as *decay equilibrium* (Figure 3.20D).

When this is considered alongside the time-scales over which river managers are interested in (1-100 years), the most appropriate scale of equilibrium is the steady-state definition identified above. This type of equilibrium in a reach relates to Mackin's (1948) definition of a graded stream whereby the reach's slope and geometry is adjusted to provide, given the prevailing discharge regime, just the flow energy necessary to transport the sediment load equivalent to that supplied from upstream. This does not necessarily imply that the morphology of reaches in equilibrium remains completely static. Instead, a steady state form of equilibrium allows for variations in reach form through local erosion and depositional processes, but over steady time (decades to centuries) a relatively consistent morphology is maintained. In these terms and at this time-scale, a reach may be considered to be in disequilibrium if, given the prevailing flow regime, it has a capacity for transport that is either in excess of the sediment supplied to the reach from upstream and local sources, or its sediment transport capacity is insufficient to transfer downstream the amount of sediment supplied to it.

This perspective on equilibrium and disequilibrium conditions is strongly related to the functionalist concepts proposed by Bull (1979) and Lane (1955b) that describe how coarse sediment dynamics depend on the balances between available and critical stream powers and sediment supply versus transport capacity. Bull (1979) defined available stream power as the power available to transport sediment load, and critical stream power as the power necessary to transport the sediment load supplied to the river channel. Where available stream power exceeds critical stream power, the additional sediment load necessary to balance the available stream power is obtained through bed degradation (Bull, 1979). Conversely, where the available stream power is less than the critical stream power, the channel responds by depositing the excess sediment on the bed (Bull, 1979). Similarly, Lane's analytical representation of coarse sediment dynamics, described by Equation 2.5, identified that a river channel would remain in equilibrium as long as the sediment discharge (Q_s) and size (D) supplied to the channel were balanced by the transport capacity of the channel's flows – controlled by flow discharge (Q_w) and slope (S). According to Lane's (1955b) analytical model, changes in any of the variables force the river into disequilibrium, triggering either degradation or aggradation.

Reach-based sediment balance models attempt to represent this concept of reach steady-state equilibrium over steady time in the general approach represented in Figure 3.21. Two existing models that are based on this approach are the Sediment Impact Assessment Model (SIAM - Biedenharn *et al.*, 2006b; Gibson and Little, 2006), and the River Energy Audit Scheme (REAS - Wallerstein *et al.*, 2006).

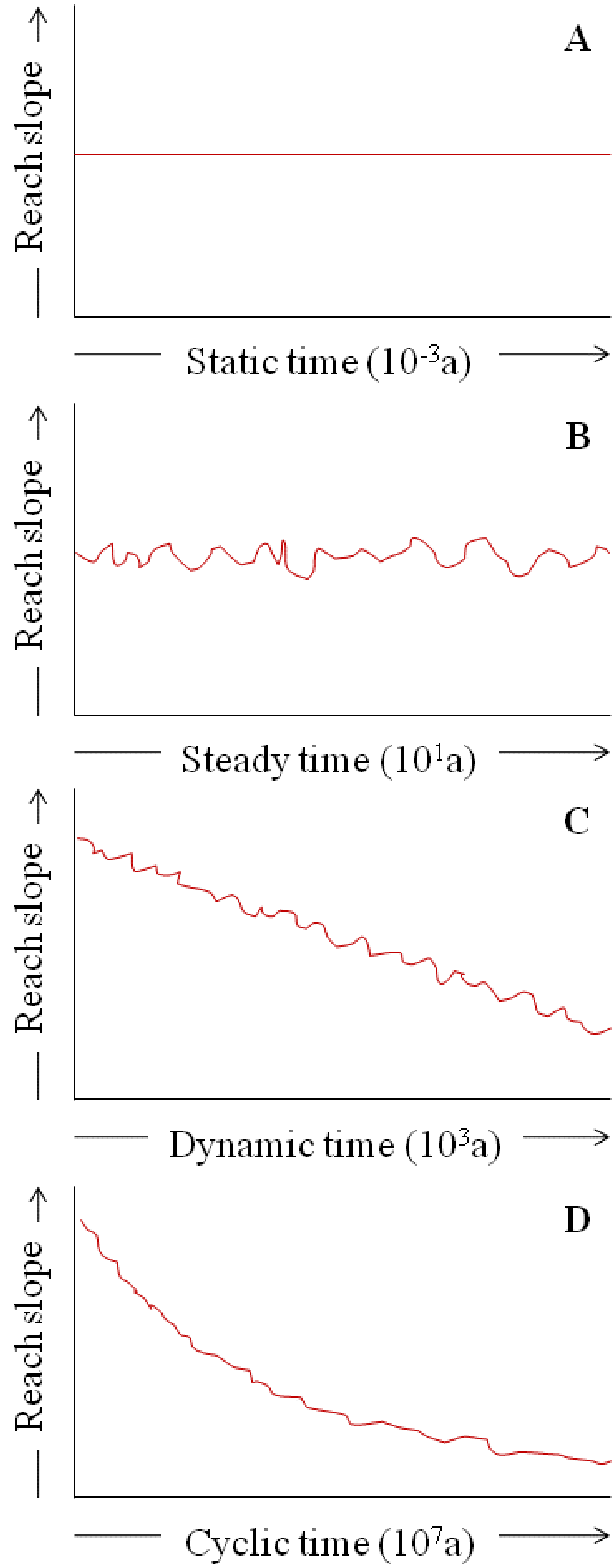

Figure 3.20 Different time-scales of reach equilibrium with reference to schematic changes in reach slope: (A) static equilibrium; (B) steady state equilibrium; (C) dynamic equilibrium; (D) decay equilibrium. Modified from Summerfield (1991).

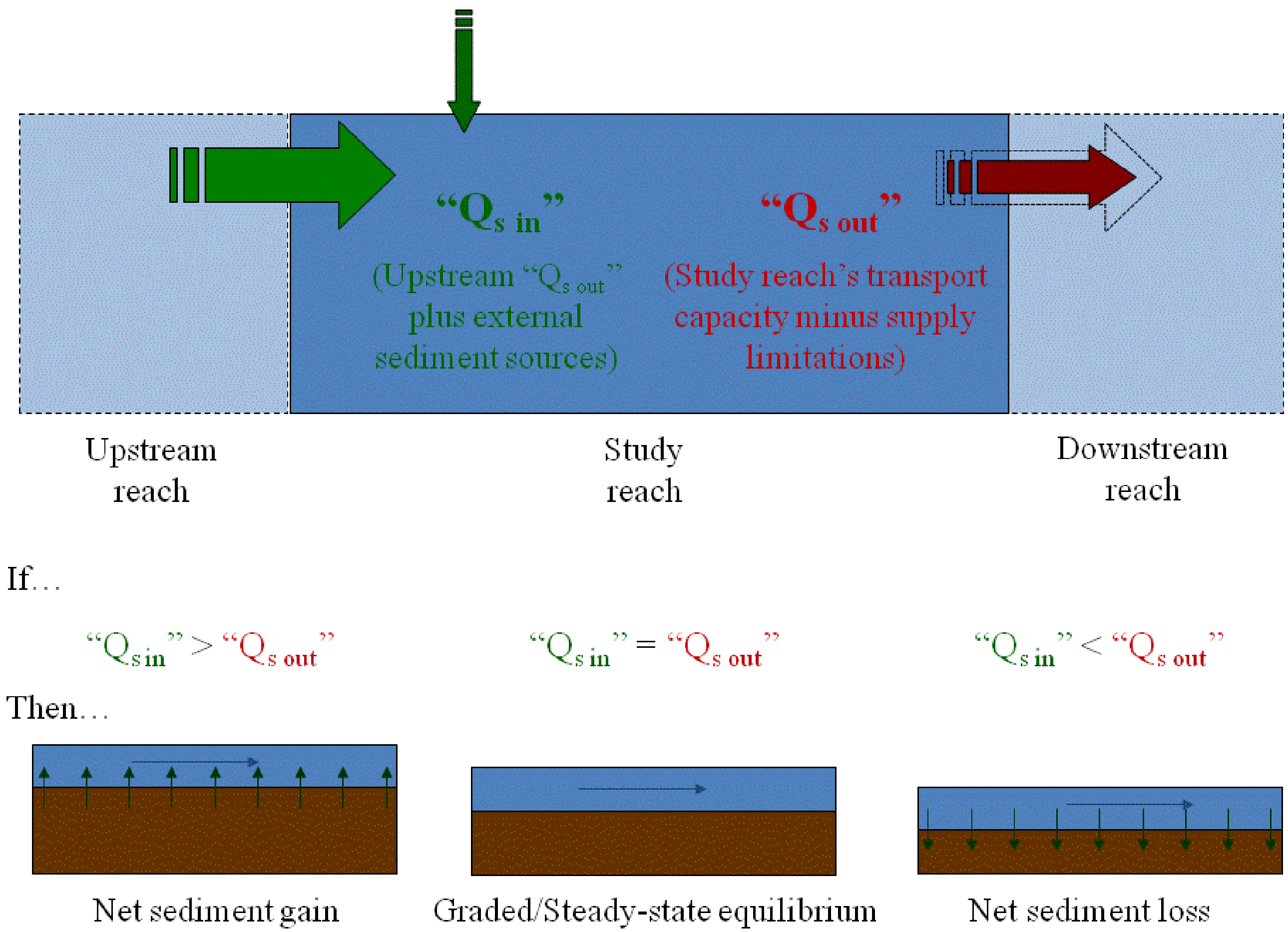

Figure 3.21 Simplified schematic of reach-based sediment balance approaches.

The Sediment Impact Assessment Model (SIAM) was developed to provide rapid assessment of the impact of sediment management activities on sedimentation trends. It combines user-defined, within-reach sediment sources with computed sediment transport capacities into a model that can evaluate sediment imbalances and downstream sediment yields on a reach basis (Brunner, 2006). SIAM is designed to provide sediment managers with an intermediate assessment tool that falls somewhere between the qualitative evaluations made by approaches like the Fluvial Audit, and the more comprehensive mobile boundary modules contained within 1-D numerical models like HEC-RAS and ISIS (FRMRC, 2006).

SIAM is available as a hydraulic design module in HEC-RAS 4.0 (Biedenharn *et al.*, 2006b). This allows users to utilise the HEC-RAS hydraulic modelling system as a means for entering data into SIAM. Unlike the mobile boundary module option within HEC-RAS, SIAM treats a stream network as a series of discrete, internally homogenous, reaches, the boundaries of which are user-defined. Sediment reaches are typically delineated based on observed locations of significant geomorphic change such as tributary junctions, changes in channel gradient, planform and geometry, and shifts in bed sediment composition. These morphological properties are then averaged within these reaches, so that HEC-RAS produces reach-averaged flow conditions. SIAM is a sediment balance model and is therefore essentially static – identifying the balance in reach inputs and outputs over a fixed time period, with no iterative modification of reach parameters. This differs significantly from the mobile bed module in HEC-RAS, which does iteratively update channel cross-sections, slopes and bed material distributions after each time-step. Therefore, whilst based on inputs from the same 1-D hydrodynamic model, SIAM represents the river channel in a manner that is far less spatially and temporally complex than the cross-section-based mobile boundary module in HEC-RAS.

Based on the reach-averaged flow conditions SIAM calculates the average annual sediment transport capacity for each reach, and compares them against the average annual sediment supply delivered to the reach. Sediment supply is based largely on the predicted output of the adjacent upstream reach, but is also supplemented by user-defined sediment inputs from local sources such as bank retreat, tributaries, and sheet erosion by surface runoff. Using the difference between the annual quantity of bed material supplied to the reach and the annual quantity of bed material that the reach has capacity to transport, a reach's bed material balance is calculated. A negative local balance indicates excess transport capacity and thus net erosion potential for a reach, whereas a positive local balance indicates excess supply and potential for net deposition (Biedenharn *et al.*, 2006b).

Usefully, the sediment computations within SIAM are sub-divided into grain-size fractions, which allows the fate of specific size sediments to be observed throughout the system. This grain size accounting also allows the discriminatory tracking of wash load and bed material load through the fluvial system. The model determines whether sediments within a system constitute wash load or bed material load based on a user-defined wash load threshold diameter, for which the default size is the D_{10} of the bed material particle size distribution in the reach in question. Downstream changes in the wash load threshold diameter permit sediment that is wash load in one reach to transition into bed material load in a downstream reach, and *vice versa*. This allows a sediment source produced by a given management practice to have little effect on channel stability in one reach where it is part of the wash load, but to have significant effect on stability in reaches farther downstream where it transitions into the bed material load (Biedenharn *et al.*, 2006b).

In a similar manner to RAT, SIAM relies on spatial and process simplifications in order to shed light on coarse sediment dynamics. Despite these simplifications, its utility to British river researchers and managers is still limited because of the data requirements necessary to run the model. Specifically, SIAM requires data for each of the sediment reaches describing the flow regime, roughness, bed material particle size distribution, and sediment loading from local and catchment sources. Information on local and catchment sediment sources is particularly problematic. However, the data necessary to define the annual loadings and calibres of material derived from channel and catchment sources such as eroding stream banks, gullies, upland surface erosion, and point sources such as sand and gravel mining operations are vital to proper operation of SIAM (Biedenharn *et al.*, 2006b). As discussed in Section 3.2, sediment data are not widely available for British rivers and their collection would require resource intensive, primary field and remote sensing work as part of any project-related or research study before SIAM could be properly applied. Further, SIAM relies on selection of an appropriate sediment transport equation from those available in HEC-RAS 4.0, to calculate the reach transport capacities. As with any sediment model, extreme caution and sound judgement based on long experience are necessary when selecting and applying these equations.

Based on difficulties experienced in applying SIAM to British rivers as part of FRMRC research (Wallerstein, 2006), researchers at the University of Nottingham developed the River Energy Audit Scheme (REAS) to identify reaches as being sediment sources, pathways or sinks (Wallerstein *et al.*, 2006). The reach-based comparison framework used in REAS is similar to that applied in SIAM but, rather than attempting to predict reach-averaged, annualised sediment transport supplies and capacities explicitly, REAS compares the difference in time-integrated excess stream power per unit bed area between a reach and its upstream neighbour.

The theoretical justification for the parameters used stems from the concept of specific stream power (stream power per unit bed area) proposed by Bagnold (1966), in which he defined stream power per unit bed area as a measure of the flow's ability to perform work on its boundary. Bagnold's stream power approach has been further developed by several authors to predict sediment movement and geomorphological adjustments in rivers (Yang, 1972; Chang, 1979; Graf, 1983; Lawler, 1992a; Magilligan, 1992; Knighton, 1999). Its popularity is largely a result of its basis in physics and its practical utility (Ferguson, 2005). It is conceptually attractive insofar as it treats rivers as transporting (and therefore work-performing) machines with explicit attention to their power and efficiency. It is also pragmatically convenient in that stream power per unit bed area can be calculated from gross channel properties (width and slope), together with the discharge provided by the catchment, without needing to know in-channel flow properties such as depth or velocity. Discharge is essentially constant between tributary junctions and may, therefore, be obtained from hydrometric records or predicted from a hydrological model, whereas depth (needed for the calculation of shear stress) is locally variable and not routinely measured.

The REAS approach is less prone to uncertainty than the models described above because it neither attempts to predict annualised sediment yields (like SIAM) or route sediment through the fluvial system (like ISIS Sediment). Instead, REAS uses excess stream power per unit bed area as a surrogate for the ability of flow to perform work through sediment transport. Stream power per unit bed area is usually expressed in watts (per unit channel length) but in REAS it is converted to an 'annualised' quantity of excess energy (for an average year in the period of flow record), or Annual Geomorphic Energy (AGE), in units of kilowatt-hours (kWh), where one kWh is the quantity of energy equivalent to a steady power of 1 kW running for 1 hour (or 3.6 megajoules of energy consumed). By making this adjustment, the output from REAS represents energy *consumption* rather than *rate* and is comparable to the more conventional measure of annualised sediment yield.

REAS then calculates the difference between AGE values (essentially, event-integrated, excess stream power per unit bed area) between consecutive reaches to indicate potential continuity or imbalance in sediment transfer. This approach was adopted because estimates made from uncalibrated sediment transport equations are associated with very high uncertainty, which is avoided in REAS through the use of an energy budget in place of a sediment budget (Phillip Soar, University of Portsmouth, personal communication, 2009[2]).

In its present form, REAS requires data input in the form of a bed material D_{50} or particle size distribution, a flow duration curve, representative channel cross-section, bed slope and channel roughness value for each user-defined reach (Wallerstein *et al.*, 2006).

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[2] Soar, P., Wallerstein, N. P. In review. Characterising sediment transfer in river channels using stream power. River Research and Applications.

Despite a key motivation of REAS's development being the need for a methodology that falls between the qualitative Fluvial Audit and the quantitative, but data intensive, mobile boundary 1-D hydraulic models, the data requirement for application of REAS still exceeds that currently available for the vast majority of British rivers. Reliable information on bed material particle size distributions is scarce, and rudimentary classifications of bed material types that are incorporated in the RHS database have been shown not only to be inconsistent with field samples (Figure 3.19), but also to provide uneven coverage of British rivers (Figure 3.8). Similarly, the available sources of channel cross-section geometry and roughness data described in Section 3.2 lack both the accuracy and coverage necessary for widespread application of REAS. Therefore, despite commendable attempts to make REAS a more practically useful tool than those previously available through simplification of spatial scale (division into reaches), and process representation (substitution of sediment with energy budgeting), it still requires too substantial an investment in data gathering to be widely useful within British river research studies and management projects.

There are also issues concerning how useful an energy budget is as a 'simplification' of catchment-scale sediment dynamics. The motivation behind the application of an energy budget instead of a sediment transport budget is clear, but is perhaps unnecessary and contradictory. By using stream power per unit bed area as a proxy for sediment transport capacity, REAS avoids the problems associated with uncertainty in calculating sediment transport rates. Rather than attempting to predict actual sediment budgets it simply identifies differences in the energy available for doing geomorphic work between adjacent reaches. Yet not only is stream power per unit bed area commonly used within sediment transport equations (Bagnold, 1966; Bagnold, 1980), but also REAS applies a critical threshold function (Ferguson, 2005) to calculate the excess power in a manner also commonly utilised within formal sediment transport equations (Bagnold, 1980; Wilcock, 2001). In summary, whilst REAS expresses its budgets in terms of kilowatt-hours to avoid its outputs being misconstrued as anything other than potential differences energy consumption between reaches, REAS's excess power is essentially an uncalibrated sediment transport function.

Further, studies have demonstrated that the relationship between excess stream power and sediment transport capacity is non-linear: typically, sediment transport capacity is related to excess stream power to the power of 1.5 (Bagnold, 1980). An example of the impact of this non-linear relationship is that, when excess stream power is integrated over the annualised flow duration curve, REAS under-represents the impact of high flow events and exaggerates the impact of low flow events. Effects like this will therefore cause REAS's output to systematically miss-represent inter-reach sediment differences.

3.3.6 Stream Power Screening Tool

Brookes (1987) used stream power as a tool to explain river channel adjustment downstream from 57 channelisation works in England and Wales. He showed that eroded sites had specific powers within the range 25 Wm^{-2} to 500 Wm^{-2}. By contrast, an absence of downstream erosion at the majority of lowland sites was assumed to be a reflection of both incompetence of increased flows to erode the bed and banks and resistance to those flows provided by the perimeter sediments, as reflected by stream power per unit bed area values in the range 1 Wm^{-2} to 35 Wm^{-2} (Brookes, 1987).

Based on these results, Brookes (1987) suggested that geomorphic thresholds exist for the response of a stream to channelisation, and that at the sites he studied, the threshold for responses led by erosional processes was associated with stream power per unit bed area values of 25 Wm^{-2} to 35 Wm^{-2}. Based on this finding, Brookes (1987) argued that this threshold could be used in conjunction with consideration of the nature of the channel boundary materials and geomorphic setting of the stream, to suggest whether rapid and adverse adjustments are likely to occur in response to channel management projects.

Brookes's method is widely applicable, as stream power per unit bed area values can be calculated from gross channel properties (width and slope), together with a user-specified, representative discharge, without needing to know within-channel flow properties such as depth or velocity (Ferguson, 2005). This makes it possible to apply the method using the data sources identified as already widely available at the catchment-scale for British rivers (see Section 3.2). However, reliance on selection of an appropriate reference discharge (Brookes recommends bankfull) introduces the need for either reliable cross-sections and expert interpretation of the bankfull stage – the availability of which is likely to limit the practical utility of the method.

Tilmore Brook in southern England may be used as an example application. This is a lowland watercourse with a straightened channel and a flow regime adversely affected by urban runoff which was undergoing severe erosion. Stream power analysis identified a bankfull stream power in excess of 35 Wm^{-2} which exceeded the threshold for channel stability (Brookes and Chalmers, 2005). Based on this, it was identified that the channel should be re-sectioned to reduce its bankfull stream power per unit bed area below the threshold value for erosional instability. Possible management solutions were identified as: reducing channel slope by restoring something approximating the pre-channelisation, meandering course; or reducing bankfull discharge by attenuating runoff from the urban catchment upstream.

However, despite the apparent simplicity of the stream power screening tool, it must be recognised that published thresholds for channel instability are strongly dependent on the environment within which they were derived, in general, and the sedimentology of the site in question, in particular (Brookes, 2007). Because of this, Brookes (2007) cautions against application of the Stream Power Screening Tool in new environments unless a database of stream power values relating to stable and unstable channels specific to that environment has first been developed.

Further, this screening approach does not take into account the sediment load supplied to the reach in question, the importance of which has been demonstrated by Lane *et al.* (1996). By focusing on the capacity of the channel to convey sediment (as represented by the proxy variable of stream power per unit bed area), Brookes's Stream Power Screening Tool accounts for just one side of

Lane's sediment balance (Lane, 1955b). A reach may have a bankfull stream power greater than the threshold identified as being critical for its particular sedimentology, but if it is subject to extremely high sediment influx then it may still tend towards instability that is depositionally-led.

In conclusion, whilst the Stream Power Screening Tool represents a methodology that is applicable using the data sources identified as already widely available at the catchment-scale for British rivers (Section 3.2), it lacks scientific rigour, making expert interpretation necessary to support sound judgement concerning its outcomes.

3.4 The need for a new reach-based sediment balance model to quantitatively account for catchment-scale coarse sediment dynamics in British rivers

A number of tools for analysing the sediment dynamics of river have been identified; with the qualitative Fluvial Audit the approach most widely applied within current British river management. However, Thorne *et al.* (2006) identified that a quantitative tool is required in order that assessment of catchment-scale sediment dynamics can interface effectively with the engineering components of strategic flood risk studies and Catchment Flood Management Plans. Further, a predictive capacity is necessary for options appraisal when considering the sediment impacts of proposed river management actions and system responses to future scenarios for environmental change. These needs restrict the utility of the Fluvial Audit approach.

Given the paucity of resources for data gathering in the great majority of British river management projects, any practical quantitative tool for application in river catchment studies must be operable within the bounds of the limited data already available, as identified in Section 3.2, whilst also maintaining the physical rigour necessary to make reliable predictions. The resources and data required to apply the majority of existing quantitative representations of coarse sediment dynamics prevents their widespread application at the catchment-scale. In particular, 1-D, mobile bed hydrodynamic models require both extensive data inputs and expensive specialist skills to support their application even at the reach-scale. Whilst sediment balance approaches like SIAM and REAS were developed with this limitation in mind and attempted to spatially simplify drainage networks through their division into geomorphic reaches, in their current form, their data requirements still exceed what is generally available.

Despite this, it is apparent that reach-based approaches like REAS and SIAM do represent a suitable framework within which to develop a new approach to accounting for coarse sediment dynamics at the catchment-scale. As identified in Section 3.3.3, dividing the drainage network into reaches simplifies the complex hierarchy of forms and processes present in the fluvial system, making it more manageable for both research and management purposes. It also significantly reduces the data required to parameterise a model.

A sediment balance approach is attractive in two aspects. First, it is conceptually attractive as it is closely linked with the theoretical definitions of steady-state channel equilibrium described in Section 3.3.5, specifically Mackin's (1948) definition of a graded stream where the slope is adjusted to provide the flow velocity necessary to transport a sediment load equivalent to that supplied from upstream. Deviation in reach sediment transport capacity from the sediment rate supplied over steady time-scales indicates a divergence from a graded condition and a movement away from steady-state equilibrium. The idea of discontinuities between the sediment transport capacities of adjacent reaches being responsible for conditions of morphological instability is evident in the literature. For example, in a study of downstream trends in channel gradient and stream power in the Bellinger catchment, New South Wales, Australia, Reinfelds *et al.* (2004) identified that many observable differences in channel sedimentology are attributable to discontinuities in downstream sediment transport. They compared the processes occurring in two channels, each of similar stream power, but with one having a high stream power reach immediately upstream and the other having had a similar stream power for a significant distance upstream. The reach downstream of a zone of high power was observed to become a zone of aggradation through deposition of the excess sediment supplied from upstream. In contrast, the reach with a similar stream power to its upstream neighbour was found to be stable.

Secondly, the reach-based sediment balance approach is practically attractive when working at the catchment-scale as it produces predictions that are far less specific than that of 1-D, mobile bed models. Rather than predicting specific morphological development within particular cross-sections, the sediment balance approach simply provides an index of whether a reach is likely to experience a net gain or a net loss of sediment during ‘steady time’. This is a more appropriate output when dealing with coarse sediment dynamics at the catchment-scale as the indeterminacy associated with the considerable number of interacting, non-linear relationships involved in process-response modelling means that deterministic predictions for individual cross-sections distributed throughout an entire river catchment are impossible (Beven, 1989; Phillips, 2003; Coulthard and Van de Wiel, 2007). When simulating system behaviour using sparse, spatially-averaged data, attempting to model fluvial processes and morphological responses at anything other than the broad-scale gives the impression of an understanding that is of greater detail than is practically realisable.

It is in this spirit that the remainder of this thesis focuses on development and testing of a new, reach-based sediment balance model to account for catchment-scale, coarse sediment dynamics in British rivers. A recurrent challenge during this development will be to ensure that it is both scientifically credible and practically operational, given the data restrictions identified in this chapter. Chapter Four addresses some of the fundamental issues met during the development of the new, reach-based sediment balance approach.

Chapter Four: Model design - developing a new reach-based sediment balance model for assessing catchment-scale coarse sediment dynamics in British rivers

4.1 Designing a new reach-based sediment balance model

While a great deal of research time and effort has been invested in gaining detailed knowledge of the processes and mechanics of sediment transport (Graf, 1971; Bogardi, 1974; Chang, 1988; Simons and Senturk, 1992), it is recognised that the complex nature of sediment transport means that a completely deterministic representation of that process is impracticable. In addition, complications associated with addressing sediment transport at large time- and space-scales preclude analysis based on approaches that begin by simulating the movement of individual grains (Biedenharn *et al.*, 2006a). It has been argued here that what is needed is a broader consideration of the sediment transfer system that reproduces its main attributes, behaviours and responses to disturbance, without attempting detailed replication of sediment transport processes *per se*. Under the general framework of reach-based sediment balance models described in Chapter Three there is significant flexibility in the choice of specific structure and procedures.

Figure 4.1 shows a 'skeleton' outline for this type of approach and identifies several issues that require careful consideration during the design of the new model. For each of these issues, thought needs to be given regarding how they can best be dealt with given the problems identified in Section 3.4 with respect to the need to strike the correct balance between scientific rigour and practical utility. The remainder of this chapter is centred on identifying the most appropriate solution to each of the issues raised, whilst taking into consideration the restrictions identified in Chapter Three.

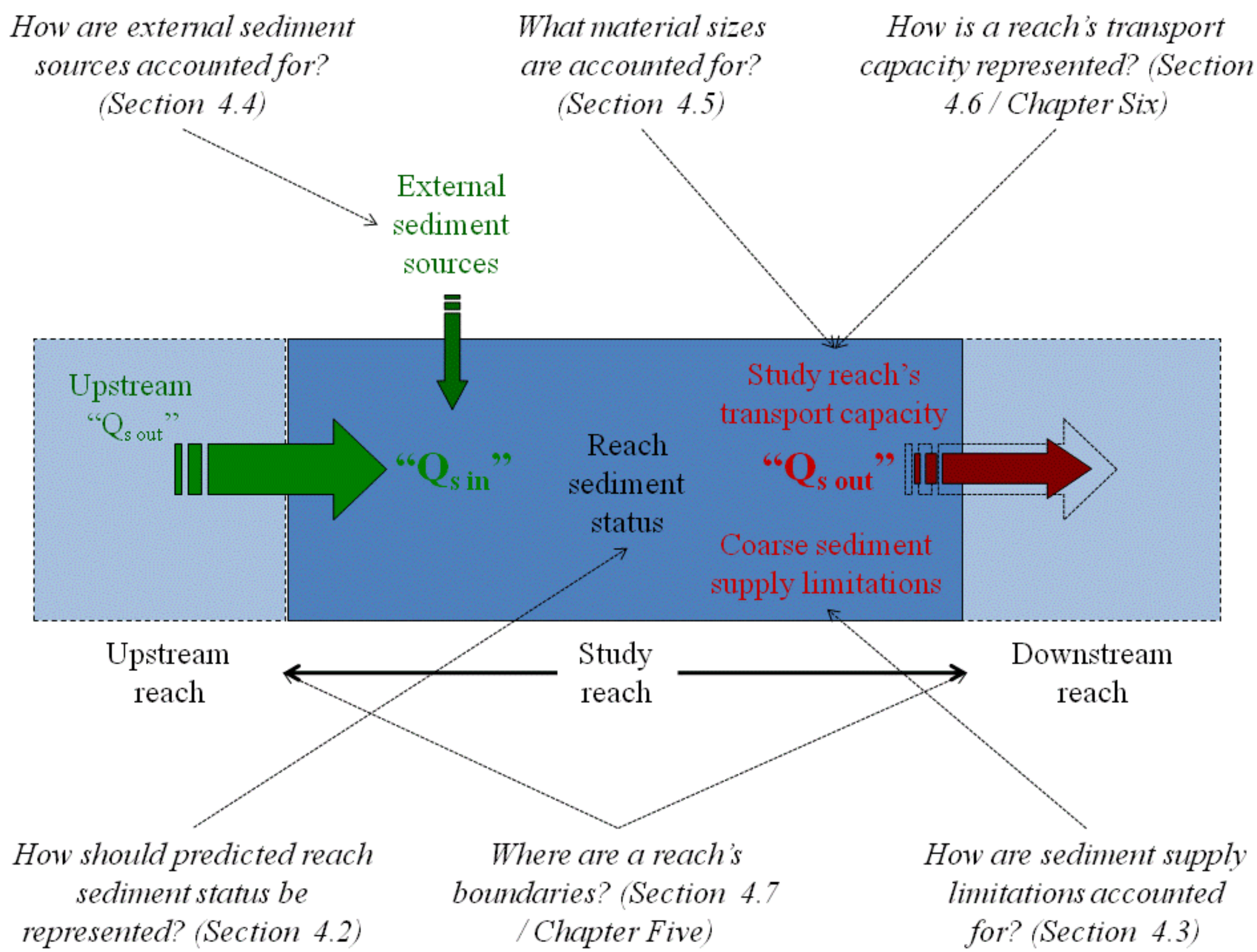


Figure 4.1 'Skeleton' reach sediment budget framework with aspects for consideration within model design.

4.2 Representation of reach sediment status

Kleinhans and Buskes (2002) comment on how an ‘underdetermination’ of earth-science theories by observation means that the reduction of earth science phenomena to physics is currently unfeasible. Causes of ‘underdetermination’ include: a) the erosion of evidence of earth surface processes; b) multiple explanations for a single phenomenon (equifinality); c) a lack of evidence to decide between competing theories; d) a lack of detailed and accurate initial and boundary condition data to run highly sensitive models; and e) chaotic system behaviour making the necessary precision of initial conditions for prediction into the future unobtainable. These fundamental ‘underdetermination’ problems restrict the ability of any approach to catchment-scale coarse sediment dynamics to confidently predict rates of erosion and deposition at specific locations. Therefore, within the new approach, reach sediment status will be output in a manner that does not infer a particular sediment transport rate, but instead represents the relative balance between the quantities of sediment predicted to enter and leave the reach during an average year.

Soar (2000) was concerned with identifying the necessary design dimensions of a restored channel based on the flow and sediment load coming in from the reach directly upstream in order to ensure that there was no net aggradation or degradation within the restored reach. In order to satisfy this goal, Soar (2000) applied a sediment budget analysis called the Capacity-Supply Ratio (CSR). This CSR was calculated as the predicted coarse material load transported out of the restored reach by the natural sequence of flow events (capacity) divided by the coarse material load transported into the restored reach by those same flow events (supply). In terms of channel restoration design, a CSR close to unity indicates a successful project design, with values greater than one indicating potential channel degradation through net loss of sediment, and values below one indicating potential aggradation through net gain of sediment. The utility of this approach was demonstrated by Soar (2000) through post-project assessment of the restoration of Whitemarsh Run, Maryland, USA. The restoration project in question involved the conversion of a previously channelised reach with low sinuosity into a highly sinuous, meandering channel with bank protection. Post-project reconnaissance revealed significant planform and cross-sectional changes following restoration, with the channel reducing its artificially constructed sinuosity by depositing sediment on the outside of the engineered bends. For all the reaches relevant to the restoration project, Soar (2000) predicted the bed material loads transported in order to find the CSR for the restored channel (Figure 4.2). A comparison of sediment supply and capacity for the restored reach revealed a CSR of only 0.64, indicating that the restored channel had the capacity to transport less than two thirds of the load supplied from upstream, with potential for approximately a third of the input load to be deposited over the medium- to long-term. This result is consistent with the observed sedimentation and aggradation in the restored meander bends and validates the application of CSR within a reach-based sediment budget approach, in this case at least. Therefore the CSR parameter will be utilised here to predict likely reach stability.

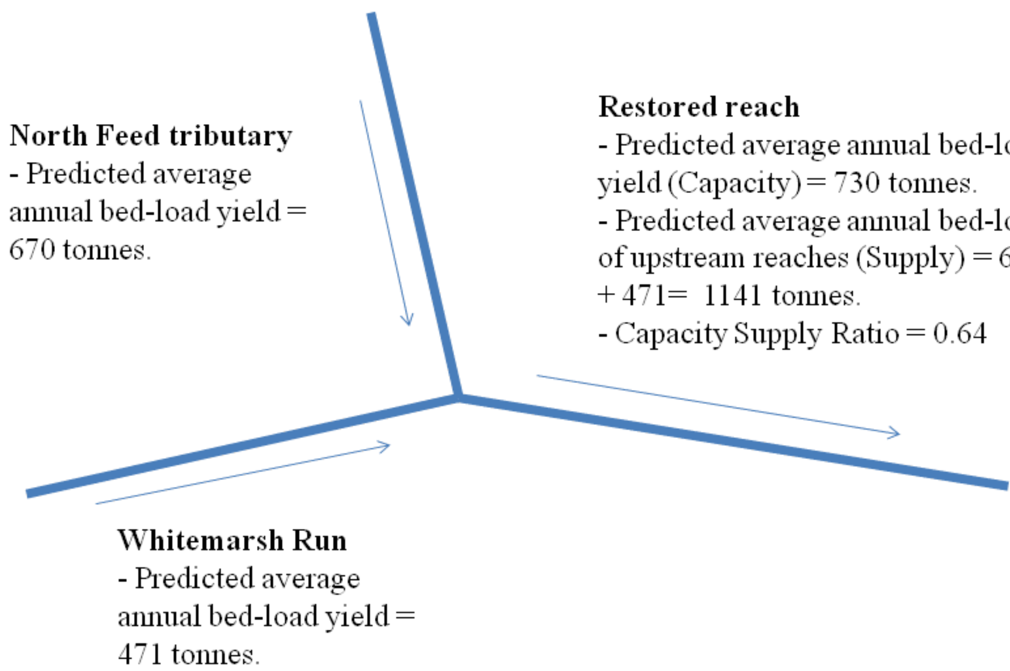


Figure 4.2 Representation of Capacity Supply Ratio (CSR) for restored reach on Whitemarsh Run, Maryland, USA Average annual CSR = 0.64 (modified from Soar, 2000).

4.3 Accounting for sediment supply limitations

4.3.1 Limitations to reach coarse sediment transport capacity

A simple distinction is often made between supply-limited and capacity-limited transport (Bravo-Espinosa *et al.*, 2003). Most of the material supplied to streams is so fine compared to the bed material that, provided it can be carried in suspension, almost any flow will transport it through the fluvial system. This material is widely referred to as the wash load or throughput load. The transport of this fine fraction is therefore controlled by the rate of supply (supply-limited) rather than the transport capacity of the flow. In contrast, the transport of coarser material that comprises the channel bed is intermittent and varies in association with flow stage. As a result, coarse material transport is generally considered to be capacity-limited rather than supply-limited. For example, Nordin and Beverage (1965) related unit discharges to unit bed material discharges of the Rio Grande near Albuquerque, New Mexico and implied that sand and coarser material move at stream capacity because they found that all bed sediment in excess of stream capacity was deposited and any deficit was replenished by bed scour. They proposed that the transport of the coarser sand and gravel in the Rio Grande is functionally related to discharge and is, therefore, transport-limited, whereas the movement of finer sediment is governed by its supply. Similarly, in recent studies of ephemeral-stream channels where sediment is abundant and non-limiting, Reid and Laronne (1995) and Lane *et al*. (1997) both found that coarse sediment transport rates are highly correlated with flow intensity, suggesting that coarse material transport is indeed transport-limited.

However, this simple division between transport- and supply-limited sediment is misleading since, whilst coarse material transport is indeed strongly influenced by the transport capacity of the flow, it can also be limited by the availability of sediment for transport. Wolman *et al.* (1997) suggested that bed-load transport in 11 Idaho streams was supply-limited based on an observed displacement of measured transport relations from predicted values associated with transport-limited streams. In fact, coarse material transport out of a reach can be restricted at two main spatial scales: limits to the supply delivered to a reach from upstream reaches; and limits to the availability of material locally within the channel.

The factors operating at each of these scales act to reduce the rate at which coarse material is transferred out of a reach below that predicted based on the transport capacity of that reach. Therefore, these factors are significant to sediment balance approaches that require estimates of the rates at which coarse material is transferred out of a reach not only to inform the sediment balance of the reach in question, but also to inform the supply of subsequent downstream reaches. The remainder of Section 4.3 considers supply limitations at each of the identified scales and how these might be represented in the new catchment-scale, reach-based, sediment balance model.

4.3.2 Restricted sediment delivery from upstream reaches

If the supply of material to the reach from upstream is less than its transport capacity then the quantity of material transferred out of the reach is limited to the amount supplied, plus any material entrained from the channel boundaries. This was clearly demonstrated by Lane *et al.*’s (1996) study of an actively braiding, pro-glacial stream where patterns of erosion and deposition were dependent not only on variations in flow discharge, but also on sediment supply fluctuations from upstream channel reaches. This type of sediment supply limitation is inherently recognised within reach-based sediment balance approaches as the sediment balance for a reach is explicitly dependent on the difference between the reach’s sediment transport capacity and sediment supply from upstream.

However, this treatment of upstream sediment supply does not fully reflect the variability present within natural sediment systems. For example, short term temporal variations in sediment supply have been recognised as common features of coarse material transport under both quasi-steady (Hoey, 1992), and variable (Reid *et al.*, 1985) flow regimes. Sediment pulses have been linked with a variety of mechanisms, but the migration of coherent bed forms is considered by some to be the most prevalent cause. As dunes pass a given point maximum amounts of transport are associated with the passage of dune peaks and smaller amounts with that of intervening troughs (Leopold and Emmett, 1976). Similarly, low-amplitude, bed-load sheets formed from the migration of heterogeneous, coarse sediments can also produce pulses (Whiting *et al.*, 1988). Nevertheless, whilst this scale of temporal variation may influence transport rate sampling strategies, it is not considered to be a significant factor within the context of a reach-based sediment model. This type of variation is likely to be insignificant over the *steady time* scale of interest within the model.

However, one temporal variation in sediment supply that is effective over the time-scales of interest to reach-based sediment balance models is that observed in the delivery of coarse sediment to the river channel network from coupled catchment sources. The events that deliver coarse sediment from catchment slopes (land-slides), and river channel banks (bank mass failures) into river channels are inherently non-uniform and episodic (Bathurst, 1987). Large, long term sediment pulses have been associated with discrete sediment inputs that are translated downstream as waves (Nicholas *et al.*, 1995). Along rivers in British Columbia, Church and Jones (1982) identified alternating sequences of sedimentation zones (characterised by wide, braided channels where large volumes of sediment are stored) and transportation zones (within which sediment is efficiently transferred to the next sedimentation zone). The cause of these sediment pulses was considered to be large volumes of material introduced by late nineteenth-century erosion of moraines. Similarly, Sarker and Thorne (2006) identified the 1950 earthquake in Assam, India as being responsible for a large pulse of relatively coarse sediment that has taken several decades to travel downstream through the Brahmaputra-Jamuna-Padma-Lower Meghna river system. Alongside these natural causes of long term sediment pulses, the supply of coarse material from the catchment can also be amplified or restricted by primary industries, notably mining and forestry. This has been particularly important for coarse sediment delivery in British rivers (Lewin, 1987; Leeks and Marks, 1997).

Temporal variability in catchment sediment delivery is important in controlling sediment supply to a reach from its upstream neighbour because of the interdependent nature of catchment sediment dynamics. The inherent and seemingly unavoidable difficulty with predicting the supply of material to a reach (r_n) from upstream is that, without the ability to measure sediment delivery rates, the only means of predicting sediment supply is to calculate the transport capacity of the upstream reach (r_{n-1}). However, as with the reach in question (r_n), the sediment transported out of the upstream reach (r_{n-1}) may itself be supply-limited. This chain of indeterminism continues up through the catchment, with the supply for each reach partially dependent on the output of the reach upstream, which is, in turn, partially dependent on the output of the reach upstream of itself. Unless there are significant transfer discontinuities within the catchment, this can continue through to the original sources of sediment. Since it has been identified that the original sources of sediment can be non-uniform and episodic over the time-scales of interest, comprehensive and accurate prediction of upstream sediment supply limitations is an unrealistic ambition.

4.3.3 Local channel boundary armouring and protection

Flow within a reach is not only able to transport the coarse material supplied to it from upstream, but also the material making up the channel boundaries of that reach. This may occur because either: the supply of coarse material into a reach is smaller than the capacity of the reach to transport sediment and so the 'excess' transport capacity is used to entrain material from the channel boundaries; or the channel boundaries are more easily entrained and transported than the material supplied from upstream. However, the ability of the reach to achieve its transport capacity by sourcing material from its boundaries can be limited, particularly from gravel-, cobble- and boulder-bed channels in which armour layers can develop.

Bed armouring occurs when a layer of coarse grains overlays a finer substrate to which it gives protection. Opinions differ regarding the formative process, but downstream and vertical winnowing, which involve the selective removal of fine particles from the surface framework are often emphasised (Thorne *et al.*, 1987; Richards and Clifford, 1991). The resultant armour layer effectively acts to limit the supply of available material so that the sediment transport rate is lower than that predicted by many transport capacity formulae.

In addition to bed armouring, a variety of other processes can also act to limit the potential sediment supply from reach channel boundaries. Reaches where the channel is formed in bedrock will be unable to fulfil their transport capacity by entraining material from the channel boundaries. Similarly, artificial protection of channel bed and banks within a reach also acts to restrict the availability of channel boundary material for entrainment.

4.3.4 Representing sediment supply limitations within a catchment-scale reach-based sediment balance model

When comprehensively ascertaining the sediment balance of a reach (r_n) it is necessary to account both for the influence of sediment supply limitations on the quantity of sediment leaving the reach in question (r_n), and for the influence of sediment supply limitations on the reach directly upstream (r_{n-1}) that impact upon the quantity of sediment entering the reach in question (r_n). As identified in the preceding sections, this interdependency results in an extremely complex sediment transfer system that is ultimately dependent on the episodic delivery of material into the channel system and the erodibility of channel boundaries. Complete representation of supply limitations within a reach is only possible if both the delivery of coarse sediment into reaches and the erodibility of reach bed and banks can be parameterised.

However, as described in Section 3.2 and shown in Table 3.2, there is a lack of data available to quantify these influences. Therefore, despite recognition of the potential importance of sediment supply limitations, a general but necessary assumption is required within catchment-scale reach-based sediment balance models of British rivers. This assumption is that if a reach's transport capacity exceeds the supply of material delivered to it, the reach will be able to fulfil its sediment transport capacity through entrainment of material from its channel boundaries.

However, if it is discovered that the entrainment of material from the channel boundaries is limited in a particular reach because, for example, it is concrete lined then, within the approach being developed, it is possible that the reach output can be limited to the supply of material entering the reach from upstream. The impact of this capability is explored further in Section 7.4.1.

4.4 Accounting for external sediment sources

4.4.1 External sources supplying coarse material

Whilst the total quantity of coarse sediment delivered to a reach (r_n) is largely dependent on transport from the reach directly upstream (r_{n-1}), there are additional sources of sediment that can contribute to the supply side of a reach sediment balance. Even if a reach (r_n) has a transport capacity greater than the supply of material delivered from the upstream reach (r_{n-1}), if there is a substantial supply of coarse material from local sources, the reach in question (r_n) may still have a Capacity Supply Ratio of less than unity. Local sources were explicitly recognised in the SIAM methodology (see Section 3.3.5) and include inputs from tributaries, eroding banks, and coupled hill-slopes. The remainder of Section 4.4 examines these sources and identifies how they can, or cannot, be accounted for in the new approach.

4.4.2 Tributaries: the importance of treating the catchment as a network when analysing sediment dynamics

Drainage network properties and river channel processes have traditionally been studied separately in fluvial geomorphology, with relatively few attempts to link the two (Knighton, 1998). There is perhaps a tendency to treat rivers as linear entities that follows from the traditional naming convention whereby a single channel path within a catchment is given primacy as the ‘main stem’, while other, shorter channels in the network are relegated to the status of tributaries and, conventionally, given different names. In fact, the head of any of the tributaries may be as many river kilometres upstream of the catchment outlet as the head of the main stem, and the contributions of water and sediment made by any of the tributaries may be as, or more, significant than that of the main stem.

In the absence of tributaries, river channels would exhibit smooth downstream trends in discharge, sediment load, bed elevation, channel gradient, channel morphology, and bed material grain size. However, because the main stem is actually part of a network, discharge, slope, width and depth display step changes at substantial tributary junctions (Richards, 1980; Knighton, 1987; Rhoads, 1987a; Ferguson *et al.*, 2006), while the downstream decrease of median bed grain size generated by abrasion and sorting is repeatedly interrupted by additions of coarser sediment from tributary inputs. A saw-tooth pattern of punctuated downstream fining is typical, with fining sequences along 'sedimentary links' (Rice, 1999) separated by upturns where coarse sediment is added from lateral sources (Church and Kellerhals, 1978; Knighton, 1980; Rice and Church, 1998).

Ferguson *et al.* (2006) used a numerical model to demonstrate the impact that tributaries can have on channel sediment dynamics. They found that, for a given calibre of sediment, aggradation is more pronounced downstream of junctions where the tributary contributes a quantity of sediment that is large relative to its discharge. In contrast, junctions where the tributary contributes a relatively small sediment flux for its discharge were found to promote degradation in the main stem downstream. These findings are consistent with an obvious qualitative physical argument and can be explained using Lane's analytical stream balance (1955a). Increases in the sediment flux from a tributary tend to overload the mainstream immediately downstream of the junction, causing local aggradation. This tendency is reversed by an increase in the transport capacity of the enlarged mainstream below a junction that increases the discharge relative to the sediment load.

The joint importance of both the sediment and flow delivered from tributary links was also earlier identified by Rice (1998) in his description of the sedimentary link concept. By examining the impact of tributaries on the downstream fining patterns of the Pine and Sukunka rivers in north-eastern British

Columbia, Rice (1998) showed that sedimentological and hydrological networks do not necessarily correspond: relatively small tributaries can be highly significant sediment sources either because of internal circumstances or because of relative conditions on the main stem. As a result Rice (1998) concluded that models which fail to account for sediment delivery from tributaries may be fundamentally inappropriate for understanding the sediment characteristics of fluvial systems. In a similar manner to Ferguson *et al.* (2006), Rice (1998) argued that it is the mismatch between the flow and sediment delivery that is important for understanding how tributaries influence the slope, grain size, planform and cross-sectional geometry of river channels.

Recognising the importance of tributaries to channel sediment dynamics, the new reach-based sediment balance approach should account for their influence. This is achieved by equating the supply of coarse material entering a reach to the output of the main stem reach immediately upstream plus the output of any tributaries that join the main stem at the upstream end of the reach. Further, all branches within a river catchment should not only be represented in terms of their input to the main stem, but their own reaches can also be modelled in terms of their local sediment balances. This is represented schematically in Figure 4.3. This type of approach may not fully account for the patchy and unpredictable arrangement of important sediment sources that Rice (1998) cites as being important to influencing the quantity of sediment supplied from tributaries, but it does enable estimations of tributary-sourced sediment input that are consistent with the simplifications made elsewhere in the model.

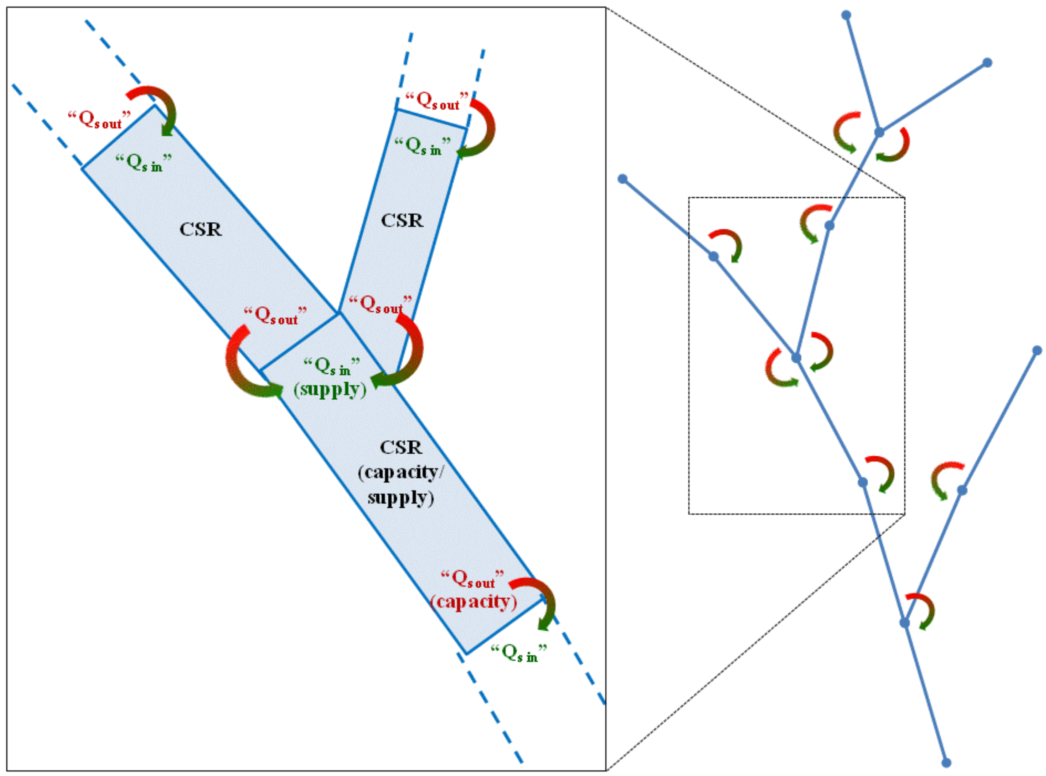


Figure 4.3 Schematic representation of treatment of tributaries in the new, reach-based sediment balance approach

4.4.3 Bank erosion

Bank erosion is a significant source of the sediment load carried by rivers, which can supply over 50 per cent of the total material delivered to the system (Simon *et al.*, 2000). As a result, coarse material supplied by retreat of a reach's banks may exert an important influence on its sediment balance. However, both the quantity and timing of inputs sourced from river bank erosion are highly variable because of a large number of controlling variables. For example, bank erodibility significantly influences bank erosion rates. However, 'erodibility' depends not only on bank material type and structure, which can themselves be extremely variable (Parker *et al.*, 2008), but also on riparian vegetation type and density. Further, similar flows acting on the same bank are often unequally effective because of the importance of antecedent conditions that control pore-water pressures and inter-aggregate cohesion. Consequently, simple correlations between discharge and bank erosion rate are often weak (Lawler, 1992a).

Various models that predict river bank stability could be used to estimate sediment loadings from bank erosion into a reach. These include the USDA-ARS Bank Stability and Toe Erosion Model (BSTEM - Simon *et al.,* 2000; Parker *et al.*, 2008). Simon *et al.* (2009) demonstrated how the BSTEM could be used to estimate annual sediment loadings in the rivers draining to Lake Tahoe, California. However, application of this type of process-based bank modelling requires detailed information not only on bank material, structure, geometry and vegetation, but also on rates of toe erosion. The limited availability of data on these bank properties for British rivers identified in Section 3.2 and shown in Table 3.2 therefore prohibits application of this type of analysis, so limiting the potential for representing the contribution of bank erosion to reach-scale sediment supply.

Although it is in any case impractical to account for bank erosion as a source of coarse sediment in the catchment-scale sediment model under development here, there are theoretical reasons for concluding that this should not negate the utility of the model. First, even where bank sources supply a substantial percentage of the total sediment load, their contribution is generally finer than that present in the bed. Hence, bank erosion contributes disproportionately to the wash load and has relatively little impact on the quantity of bed material load which is of central importance to coarse sediment dynamics and channel morphology. Second, and more importantly, the medium to long term supply of sediment from river bank erosion is itself dependent on, rather than being independent of, coarse sediment dynamics. Thorne (1982) demonstrated theoretically that the rate of bank retreat is controlled by the state of basal endpoint control. This means that the rate of bank retreat depends on the rate at which the sediment derived from bank erosion and failure is entrained and transported downstream from the 'toe' of the bank by flow in the channel. The wash load component is easily removed, but removal of the coarser fraction may be transport-limited. It follows that the rate of bank sediment supply is regulated by the capacity of the near bank flow to entrain and transport coarse sediment. Recognising this, it is unnecessary to regard material delivered from bank erosion as an additional, independent source of the coarse sediment supply into a reach: bank retreat can justifiably be considered as an extension of bed scour and just one of several ways in which a reach can adjust to having excess transport capacity for coarse sediment in relation to the supply from upstream and catchment sources.

4.4.4 Hill-slope coupling

The quantity of material delivered from hill-slopes varies with location in a catchment, generally moving from ‘strongly coupled links’ in steep, narrow headwater valleys to ‘completely buffered links’ in low gradient channels crossing wide floodplains (Rice, 1994). With increasing distance downstream, the degree of coupling generally declines since larger discharges increase the significance of fluvial relative to hill-slope activity, and wider floodplains progressively buffer the active channel from hill-slope inputs. In Section 3.2.6 it was identified that in upland basins, where stream channels are closely ‘coupled’ to adjacent hill-slopes, a range of sediment sizes significant to sediment dynamics are delivered to the channel at the slope base. These deposits locally alter the morphology of streams and increase the supply, transport and storage of coarse sediment within the channel network (Benda and Dunne, 1997a). However, as recognised in Section 3.2.6, whilst models have been developed that estimate the relative likelihood of sediment delivery into channels, reliable, quantitative prediction of material supplied to a reach from the surrounding hill-slopes is an unrealistic goal, especially given the lack of data currently available for British catchments.

As in the case of coarse material supplied by bank retreat, in addition to the practical reasoning behind choosing to neglect hill-slope sources in the new model, there is also some theoretical justification for doing so. Conventional treatment of hill-slope - channel interactions focuses on slope stability and connectivity to the channel in governing sediment yield and delivery. However, the transport capacity of fluvial processes operating in the channel at the base of the hill-slope may be the factor controlling the rate of sediment supply in the medium to long term. This is the case because fluvial processes determine the state of basal endpoint for the entire hill-slope and hence are a key to controlling slope profile and stability *via* lateral undercutting and vertical incision or aggradation. Reaches experiencing a net deficit of basal sediment are associated with the development of convex slope profiles as the channel utilises its excess transport capacity through degradation of the bed adjacent to the hill-slope. In contrast, those experiencing net accumulation of sediment at the base develop more concave profiles as the flows within the channel are unable to remove all of the sediment supplied by slope retreat, leading to aggradation and/or lateral bar or berm building (Richards, 1977). Therefore, as with bank retreat, the quantity of coarse material supplied from hill-slopes can be treated as another one of several ways in which a reach can adjust to having excess transport capacity for coarse sediment in relation to the supply from upstream and catchment sources.

4.5 Accounting for bed material size

The rate at which sediment is transported by flow is highly dependent not only on the intensity of the flow, but also on the size of the grains available for entrainment (Gilbert, 1914). As a result, the majority of sediment transport equations (including that developed here in Chapter Six) include a sediment size term. The explanation for this is simple: larger grains have greater submerged weights making them intrinsically less mobile. In a gravel-bed river, the lower mobility of coarser grains is partially offset by their over-exposure in the armour layer and therefore mobile bed models attempt to account for differences in the mobilities of different grain sizes in the active layer by routing them separately, based on the flow's transport capacity for each size fraction.

Within existing reach-based sediment balance models, there are two different ways to account for sediment grain size. The first is to follow the approach adopted by REAS, which will be referred to here as the 'static sediment size approach'. REAS calculates a reach energy budget based on excess stream power per unit bed area values for the different size fractions present in the reach's bed material, without reference to the grain size distribution of material supplied from upstream. The second approach, adopted in SIAM, is referred to here as the 'dynamic sediment size approach'. SIAM computes transport capacity using not only the grain sizes present in the bed of the reach in question, but also those of the sediment delivered from the reach upstream. Hence, the dynamic approach accounts for the impact of sediment transfers between reaches on the capacity of each reach to transport coarse sediment.

As identified in Section 3.2.5, lack of sediment data eliminates the possibility of representing the effects of bed material gradation on sediment transport capacity using either of these approaches in practice. There is, however, a fundamental argument concerning whether the size and gradation of bed material should be regarded as an independent variable affecting coarse sediment dynamics over the steady time-scale that is the focus of the new, reach-based sediment balance approach. This argument is unpacked and examined in the remainder of this section.

Bed sediment sizes and gradations vary at several scales within the fluvial system: from downstream fining over the length of a river's long profile, to sediment sorting between pools and riffles and even within individual bars. The most obvious manifestation of sorting occurs at the catchment-scale through a downstream reduction in the median bed material grain size. Longstream sorting of river gravels is commonly represented by an exponential function of downstream distance:

$$D = D_0 e^{\alpha L}$$

Equation 4.1

where D is some characteristic particle size (usually the median or mean particle size of the surface material), D_0 is the initial value, L is distance downstream, and α is an empirical diminution coefficient ($\alpha < 50$) (Powell, 1998). Three suites of processes have been identified as potential causes of downstream fining: abrasion, hydraulic sorting and weathering. Weathering by both chemical and physical means can cause substantial particle disintegration if material is stored for long periods in exposed sites, but its overall contribution is considered to be small relative to the other two processes (Powell, 1998). Abrasion is a summary term covering a range of mechanical actions and as such is very difficult to represent, although Parker (1991) developed a theoretical model demonstrating the potential impacts of one particular part of the process. Hydraulic sorting operates through a combination of selective entrainment, differential transport and selective deposition (Powell, 1998).

Abrasion had traditionally been regarded as the dominant process responsible for downstream fining, but experiments using abrasion tanks in the mid-20th century demonstrated that the reduction in size and weight of coarse particles occurs over a significantly shorter distance in a natural stream compared to the ‘distance’ of travel required to produce a similar result in an abrasion tank (Kuenen, 1956). Nevertheless, Schumm and Stevens (1973) argued that a particle can vibrate in place without downstream movement so that natural rates of downstream fining could be accounted for by abrasion processes. These findings, together with the hypothesis that all sizes in a mixture have near-equal mobility (Parker *et al.*, 1982; Andrews, 1983) suggested that hydraulic sorting was not particularly important in causing downstream fining, and that abrasion was the dominant process. This idea that abrasion was responsible for downstream fining, and was therefore independent of local channel slope, also reflected a past emphasis on the concept of the graded river (Mackin, 1948); the implicit assumption being that the slope required to maintain transport continuity decreases in the downstream direction in response to an independently generated decline in grain size. This assumption was supported by field evidence demonstrating that catchment-scale variations in channel slope are correlated with bed material size. As bed material size reduces in the downstream direction, a reduced channel gradient is required to transport the imposed sediment size (Charlton *et al.*, 1978) and overcome the imposed channel roughness (Leopold and Bull, 1979). Therefore, because slope was considered to be dependent on grain size, within a uni-directional functionalist perspective grain-size had to be controlled by something else; the obvious candidate being abrasion.

However, Ferguson *et al.* (1996) have more recently described pronounced fining over a short distance in a Scottish river where measured abrasion rates were far too small to explain the observed rate of reduction in grain size with downstream distance. Bed-load traps and the dispersion of magnetic tracer pebbles in six sub-reaches both showed a degree of size sorting during transport. The downstream fining trends observed by Ferguson *et al.* (1996) were also closely approximated by simulations using a numerical sediment routing model that routed material by size fraction. These combined experimental and model-based results suggested that hydraulic sorting was an important explanation mechanism for downstream fining.

In fact, similar findings had been reported earlier by Rana *et al.* (1973) who showed that, for a given long-profile, discharge, and input sediment size distribution, multiple fraction point-to-point sediment transport calculations resulted in an exponential bed material size reduction in the downstream direction caused by the downstream decline in stream energy as the long-profile slope diminishes.

Based on the findings of Rana *et al.* (1973) and Ferguson *et al.* (1996), it can be argued that, rather than slope adjusting to bed material size, bed material size is actually the dependent variable, being controlled wholly by downstream changes in stream energy. The findings of Frostick and Reid (1979) support this proposal, although they were made in a different context: they identified an unusual downstream *increase* in grain size in semi-arid washes where slope was uniform though discharge increased downstream. They interpreted this trend as resulting from a downstream increase in flow energy and transport competence, resulting in a coarser bed.

In nature, rather than just one process causing downstream fining patterns, the exponent α in Equation 4.1 actually reflects the undifferentiated effects of both abrasion and hydraulic sorting, with their relative importance conditioned by the lithology and particular coarse sediment dynamics of the system under investigation (Powell, 1998).

Catchment-scale downstream trends in sediment size reduction are often disrupted by material supplied to the channel from local sources such as coupled hill-slopes and tributary inputs (Rice, 1994; Rice and Church, 1996; Rice, 1999).

Where a sequence of tributaries enters a main stream exponential decreases in grain size are interrupted at each junction. Tributary junctions often exhibit a step increase in bed grain size, the magnitude which is related to the relative sizes of main stream and tributary bed material at each confluence (Knighton, 1980).

Whilst the supply of material from tributaries and hill-slope sources represent examples of the type of stochastic delivery that can influence bed material size, tributary inputs can also have a secondary influence that is driven by the changes in coarse sediment dynamics that occur at junctions. As noted earlier, Ferguson *et al.* (2006) used a numerical model to predict morphological and sedimentary changes downstream of tributary junctions in relation to variations in balance between the water and sediment fluxes supplied by the tributary. Ferguson *et al.*'s modelling results showed that relatively high ratios of water to sediment flux contributed by the tributary caused degradation and sediment coarsening downstream of the junction, whilst relatively low ratios of water to sediment flux were predicted to cause aggradation and sediment fining.

Reach-scale sediment sorting associated with pool-bar units is also superimposed on catchment-scale downstream trends of decreasing particle size (Powell, 1998). The morphology and sedimentology of pool-bar units often reflect the complex erosional and depositional histories of their formation. Riffle bars tend to have coarser bed material than adjacent pools; this being attributed to local sorting mechanisms (Keller, 1971).

Local streamwise sediment sorting along gravel bars has also been identified within natural streams (Bluck, 1987). Selective deposition has been cited as being responsible for variations in bed material size at this scale, due to continual interaction between the moving bed-load and the texture of the bed surface (Powell, 1998). Differences in bed height created by heterogeneous sediments of natural river-beds generate a turbulence intensity and scale that control the size of clasts which can remain on the surface in two ways. First, flow turbulence promotes the removal of relatively fine grains from an initially poorly sorted deposit. Second, the turbulence scale and intensity may create a 'turbulence template' (Clifford *et al.*, 1993) in which only those clasts large enough to tolerate the local turbulence can be deposited. For example, the rough surface of a depositional bar creates a coarse pocket geometry that encourages the deposition of similar sizes and decreases the likelihood of finer particles settling due to increased turbulence around the coarse clasts. Therefore, relatively fine particles 'rejected' at the bar head are transported downstream to the bar tail, where they may be deposited, creating down-bar fining (Powell, 1998). Bluck (1987) suggested that sorting at the bar-scale contributes substantially to more general downstream trends, a hypothesis for which there is some quantitative support (Clifford *et al.*, 1993). Certainly, sorting at a large scale must in some way reflect the cumulative effect of multiple sorting mechanisms operating at successively more local scales, an argument echoed by that of Lane and Richards (1997) in their commentary on the important influence that short term, small-scale processes exert over the longer-term aspects of landform behaviour.

It is apparent from the above that variations in bed sediment size at a range of spatial scales within fluvial systems can be considered both a dependent as well as an independent variable within the process-form framework that governs sediment dynamics and channel morphology. For example, at the catchment-scale bed material size can be identified both as responding to changes in stream energy, based on the concept of hydraulic sorting, but also as driving changes in stream energy, based on Mackin's (1948) idea that channel gradient, and therefore stream energy, adjusts to bed material size. At a much finer scale, selective deposition of sediment of different sizes is dependent on the sediment sizes already present on the surface of a bar. Further complicating the spatial distribution of bed material sizes along a river is the stochastic delivery of sediment of various fractions into the channel by tributaries. As a result, the composition of the bed at any point is the spatial and temporal double integral of all past delivery and transfer events in the fluvial system. The complexities of these interactions at different scales are poorly represented within both evolutionary and functional approaches to explaining coarse sediment dynamics, though they may be better appreciated using the systems approach pioneered by Chorley (1962) and Schumm (1977).

As outlined in Section 3.3.5, a reach-based sediment balance approach represents coarse sediment dynamics in a time independent or steady manner, with no representation of the process-form and process-response feedback mechanisms that operate in the fluvial system. Therefore, despite the complexity associated with these interactions, when using a reach-based sediment balance approach it is both necessary and justifiable to represent coarse sediment dynamics using only those uni-directional, causal relationships that dominate and explain system behaviour over steady time-scales. It is therefore necessary to consider which aspects of the alluvial system should be treated as the driving variables and which should be treated as the response variables in the context of the reach as a spatial scale and steady time as a time-scale. As was first recognised by Schumm and Lichty (1965), causality depends upon the scale perspective at which the fluvial system is examined. In sediment *transport* analysis, the response variable is the quantity of bed material moved per second and the key driving variables are a measure of flow intensity and the size of sediment available for entrainment from the bed surface. However, at the longer temporal and larger spatial scales associated with sediment *transfer* through the fluvial system, it can be argued that the bed sediment size should be considered as responding to sediment transport processes rather than driving them.

It has been identified above that, at the catchment-scale, bed material size and channel morphology both drive and respond to coarse sediment dynamics. However, it has also been suggested that changes in sediment size have faster relaxation times than changes in other aspects of the fluvial system. For example, Ferguson *et al.* (1996) identified that the Allt Dubhaig was able to adjust its bed material size far more rapidly than the morphological adjustment otherwise required for equilibration. Similarly, Simon and Thorne (1996) showed how rapid adjustments in bed roughness and mobility dominated process-response mechanisms operating in the North Fork, Toutle River following the eruption of Mount St Helens. In truth, neither channel slope nor grain size is a wholly independent or dependent variable within sediment dynamics as they influence each other through complex, non-linear feedback relationships (Ashworth and

Ferguson, 1986). However, it is proposed on the basis of the arguments rehearsed here that the bed material grain size should be treated as a dependent variable given the catchment (~100-1000km^2) and steady-state (~1-100yrs) space and time-scales relevant to this study.

As a result of the above it could be concluded that no representation of bed material size is necessary within a catchment-scale steady-state representation of coarse sediment dynamics: if sediment supply from the channel boundary is assumed to be independent of its grain size then between reach transport differences are purely a function of differences in hydraulics. Taking this line of argument the reach capacity supply ratios described in Section 4.2 could be calculated on the basis of an annual energy budget, like that produced by REAS, rather than a sediment transport budget. However, as identified in Section 3.3.5, there are issues concerning how useful an energy budget is as a 'simplification' of catchment-scale sediment dynamics. This is as studies have demonstrated that the relationship between hydraulic parameters and sediment transport capacity is non-linear: for example, sediment transport capacity is related to excess stream power to the power of 1.5 (Bagnold, 1980). An example of the impact of this non-linear relationship is that, when excess stream power is integrated over the annualised flow duration curve, REAS under-represents the impact of high flow events and exaggerates the impact of low flow events. Effects like this will therefore cause an approach based purely on hydraulic parameters to systematically miss-represent inter-reach sediment differences. As a result, it is necessary to employ some form of sediment transport relation.

Consequently, whilst classifying the bed material size as a dependent variable within this study's representation of coarse sediment dynamics at the catchment-scale eliminates the need to specify bed material sizes for each of the modelled reaches, it still necessary to incorporate some form of representation of bed material grain size for use in sediment transport calculations. A potential solution is to apply a downstream relationship relating bed material size to either distance downstream (as in Equation 4.1) or stream energy (represented by slope and/or discharge). However, it is argued here that this type of representation is inappropriate as it is based on the assumption of a channel that is in an average or equilibrium state. As with the use of hydraulic geometry relationships to estimate the channel's cross-sectional dimensions (see Section 3.2.2), this approach to estimating local bed material sizes would bias the model towards a representation of a graded coarse sediment system. Instead, it is proposed that, since bed material size is to be treated as a dependent variable, it should be set as a constant for all reaches in the modelled fluvial system. Only in this way can the impact of downstream changes in stream energy on reach status, including bed material size, properly be evaluated. This representation of bed material size marks a clear departure from the convention adopted in previous reach-based, sediment balance models and, therefore, its impact on model outcomes is explored and evaluated in Section 7.4.2.

4.6 Representation of reach-scale coarse sediment transport capacity

Quantification of the coarse sediment transport capacity in each reach is necessary not only to calculate the local capacity, but also to determine the supply of sediment delivered to the next reach downstream. Attempts to derive a reliable bed-load transport formulae have occupied river engineers and scientists for over a century and continue unabated. Given the substantial expense involved in collecting bed-load transport data, and the need to predict sediment transfer rates for planning purposes, transport formulae are widely applied as predictive tools. These transport formulae are constructed on the basis that it is possible to describe the rate at which bed material is transported in terms of measurable hydraulic and sedimentological variables. Yet, despite the extensive research efforts of the past century, which have produced numerous rigorously derived sediment transport equations, there remains considerable difficulty in consistently applying any of these formulae with a level of accuracy that is deemed acceptable. This is because each sediment transport formula has been developed specifically for a given set of environmental conditions, and no equation performs consistently well under all transport conditions (Gomez and Church, 1989). This means that mobile bed models generally include a choice of several sediment transport equations for use under different circumstances. For example, seven different transport functions are currently available in HEC-RAS: Ackers and White (1973), Englund-Hansen (1967), Laursen (1958), Meyer-Peter and Muller (1948), Toffaleti (1968), Wilcock and Crowe (2003), and Yang (1972). However, this situation not only results in a marked lack of consistency, but also can create confusion on the part of the user when trying to decide which transport relation to apply.

As identified in Section 3.3.5, this state of affairs led Wallerstein *et al.* (2006) to utilise stream power per unit bed area as a surrogate for sediment transport capacity in REAS. As an alternative to this type of approach, and to overcome some of the limitations with existing sediment transport equations, an objective of this thesis was to develop a new, general relationship for coarse material transport capacity that is consistent across all environmental conditions. The development of this relationship, and identification of how it may be calculated at the catchment-scale is the focus of Chapter Six.

4.7 Identification of reach boundaries

In any reach-based approach it is important to give careful consideration to the means by which reach boundaries are identified. As the variables of interest are reach-averaged, the location of reach boundaries impacts directly on the model inputs, and consequently the outputs. When applying the reach-based Riverine Accounting and Transport model (RAT) to the Los Alamos Canyon, Graf (1996) sought to divide the system into reaches with internally consistent processes and forms that were noticeably different to those of neighbouring reaches. He used geomorphological properties such as channel pattern and dimensions to define these functional reaches. In effect, Graf (1996) was identifying reach boundaries subjectively, based upon his detailed *a priori* knowledge of the spatial variability of channel morphology throughout the system. Similarly, the reach boundaries applied by users of SIAM are user-specified and hence depend on the modeller’s prior knowledge of catchment morphology. This type of approach to reach delineation has its limitations, not just because of its subjective nature, but also because it relies on the existence of reliable information on catchment geomorphology, something that cannot be assumed in contemporary river management. Where pre-existing information is insufficient for suitable boundaries to be identified in this way, a substantial investment of time and money in catchment reconnaissance is required, which is often infeasible. Yet, unless in-depth knowledge of the catchment is obtained, user-designated reaches may be unrepresentative and, consequently, impact detrimentally on model outputs.

Clearly, an alternative, scientifically-sound means of delineating reach boundaries objectively and appropriately is desirable. This is explored in Chapter Five, which identifies issues concerned with the definition of a reach conceptually, before examining reach definitions that have been commonly applied in river research and management. Based on one of these definitions, options for defining reach boundaries automatically are evaluated and the approach most appropriate for reach-based assessment of sediment dynamics at the catchment-scale is selected.

Chapter Five: Defining a reach - automatic delineation of functional river reach boundaries for a sediment balance model

5.1 Introduction

This chapter addresses the definition of a ‘reach’ conceptually, before examining a number of statistical methods that could be used to detect reach boundaries. These statistical methods are currently used within geology to aid identification of stratigraphic units. The suitability of each of these methods is assessed using a univariate test dataset of predicted bed material transport capacities along the main stem of the River Taff in South Wales. Based on this assessment, a preferred method for delineating river reach boundaries is identified. Finally, in addition to its application to reach-based sediment balance approaches, further applications of the selected reach delineation method are considered.

5.2 The pervasive yet obscure nature of ‘the reach’

Use of the ‘river reach’, as a scale-related term of reference, is widespread in both the academic and professional river research and management communities. In fact, its use is ubiquitous across sub-disciplines and across geographical regions, as evidenced from the following series of quotations: *“The bed-load formulae examined here are all one-dimensional equations parameterised by* ***reach-average*** *hydrological and sedimentological variables”* (Barry *et al.*, 2004: 18); *“For all sites the flow cross sectional data were averaged from measurements made at several cross sections along a* ***reach****…”* (Bathurst, 2002: 18); *“…framework for modelling size selective transport and sorting, capable of being implemented in an RCM at the* ***reach-scale****”* (Brasington and Richards, 2007: 174); *“For the goodness of fit, data were compared first, for the entire* ***reach****, and subsequently for riffle and pool* ***sub-reaches****.”* (Clifford *et al.*, 2005: 3635); *“PHABSIM assesses the habitat ‘performance’ of a* ***reach*** *by defining its ‘usable area’ for a particular (target) species, based on a function of* *discharge and channel structure."* (Emery *et al.*, 2003: 534); *"Information on the magnitude and variability of flow regimes at the river **reach** scale is central to aspects of water resources and water quality management."* (Holmes *et al.*, 2002a: 721); *"The overall effect on catchment-scale flood generation will be a function of the spatial location and extent of the landscape areas and river channel **reaches** affected"* (O'Connell *et al.*, 2005: 14).

This pervasive use of the reach results from the need for a manageable, scalable reference unit with which to represent patterns of spatial uniformity and variability present in natural river systems where the interrelations between forms and processes are inherently scale-dependent, and where this scale dependency has some form of functional value. The reach, as a coherent unit whose length can be scaled on the size of the fluvial system of which it is a part, represents a means of simplifying the drainage network into a series of distinct and manageable units. For example, in order to collect information on UK river habitat status, the Environment Agency's River Habitat Survey involves the inspection of the physical structure of thousands of individual *reaches* at locations on rivers all over the UK (Raven *et al.*, 1998b). Reach-based habitat information is used to provide national coverage based on standard techniques and uniform units of assessment. Similarly, hydrologists often utilise the river reach as a reference-scale within macro-scale hydrological models. In order to operate at the broad-scale, these models simplify the catchment network into a series of interconnected reach-based 'building blocks' (Paz and Collischonn, 2007). For geomorphologists, the reach represents a means of simplifying forms and processes that vary and interact over a continuum of spatial scales. This is evident explicitly in the type of reach-based sediment balance approach considered here. Within this type of approach, the reach-averaging is used so that the highly complex and physically indeterminate sediment transport processes and mechanisms that operate at the micro-scale can be represented as interactions between channel segments that represent the sediment transfer system schematically.

Despite the prevalence of the term 'reach' within river science and management, its definition is far from consistent. The majority of studies fail to define their concept of a reach, and in those that do, there is a marked lack of consistency. The Environment Agency's RHS reaches are a standard 500m in length, yet hydrologists involved in broad-scale modelling often use the term to represent an arbitrary unit based on the length of main stem channel between consecutive tributary junctions in the drainage network (Hellweger and Maidment, 1999). Contrasts in usage are present not only between sub-disciplines, but also within sub-disciplines. For example, within the field of geomorphology, a reach has been defined as: having a minimum of length of 10-20 channel widths - in the classification of mountain channel morphologies (Montgomery and Buffington, 1997); falling between tributary junctions and grid cell boundaries - in a catchment-scale sediment routing model (Benda and Dunne, 1997b); and, a geomorphologically homogeneous stretch of river, the boundaries of which are defined by observed changes in channel morphology (Eyquem, 2007). In fact, the only definition that can completely encompass all observed usages of the term reach is 'a length of river'!

Clearly, progress in any field of science will be hindered by a lack of conformity between definitions of a commonly used term. As a simplified example, within a single project, one fluvial geomorphologist may perform a reach-scale channel morphology survey over ten channel widths that is to be used by another fluvial geomorphologist within a piece of modelling software whose reach length is 1 km. Contemporary river science has seen calls for a shift towards a fully integrated multidisciplinary approach to catchment management driven, in particular, by the European Water Framework Directive (Harper and Ferguson, 1995; Newson, 2002; Raven *et al.*, 2002; Eyquem, 2007; Orr *et al.*, 2008). In this context, inconsistent use of the term 'reach' that is applied widely across all branches of river science represents a major potential obstruction to the development of integrated river management.

5.3 Operational versus functional definitions of reach boundaries

Existing definitions of reaches currently fall into three major types: operational definitions that describe reach lengths in terms of a set spatial length, for example 500m or 10 channel widths; morphological definitions that describe reach lengths based on channel or network form, for example between tributary junctions; and functional definitions that describe reach lengths based on the distance over which a certain fluvial process operates or at which a specified channel form recurs. When looking for consistency, an operational definition of constant length initially seems the obvious choice – a reach is a stretch of channel 1km in length, for example. However, while fixed length definitions of a reach offer consistency, they lack the flexibility to be easily transferred between rivers of different scales, and if they do map onto significant channel forms or processes they do this purely through serendipity. Not only may a uniform reach length definition of 1km be unsuitable for applications where the topic of interest varies over scales of 100m or 10km, but also the assigned reach boundaries are unlikely to occur at natural breaks in the forms or process of interest. As a result, operationally defined reaches often have significant internal inconsistencies in the form or process of interest, making reach-averaged representations potentially unreliable and inter-reach or inter-river comparisons potentially meaningless.

Conversely, both morphological and functional reach definitions are intrinsically inconsistent in terms of reach length, even within a single study. Within fluvial geomorphology, a channel reach is often defined as a stretch of river composed of one or more, largely homogeneous geomorphological units, the boundaries of which are defined by significant changes in forms and processes (Eyquem, 2007). For example, when Graf (1996) identified 11 reaches along the ~20km long Los Alamos Canyon in New Mexico, they ranged in length from 61m to 4568m. Yet, despite their irregular lengths these reaches were consistent in terms of their definition: they each represented specific and identifiable channel segments with processes and forms that were internally constant and could be differentiated from those in neighbouring segments. Definitions such as this therefore are consistent (in terms of geomorphology) yet flexible (in terms of length) as a means of dividing the fluvial system into reaches. As a generic methodology, defining reaches as lengths of channel within which forms and processes are more, rather than less, similar has the potential to be utilised across all river science disciplines. By consistently assigning reaches based on minimising within reach variation in the form and process of interest, riverine researchers and practitioners can more easily justify the assumption that in a catchment-scale representation of the fluvial system, reaches are lengths of channel with homogeneous properties. It is this assumption that underpins the simplification of micro-scale complexity that makes the reach such a useful concept for catchment-scale research and management.

5.4 Identification of functional reach boundaries

A major obstacle to practical application of functional definitions of river reaches is that they generally require detailed *a priori* knowledge of the system in question in order to identify where the functional reach boundaries lie. In Graf's (1996) study, this was possible since he was dealing with a relatively small, and intensively studied research catchment. In many river management applications, this is not the case – reach boundaries need to be identified without recall to the resources necessary to reconnoitre the catchment in detail. Therefore, if functional definitions of reach boundaries are to be widely applied, a means of reach delineation is required that does not require detailed *a priori* knowledge. Fortunately, the quantity and quality of relevant data that is now available means that it is possible to search for reach boundaries using statistical techniques. For example, in their study of planform dynamics of the Lower Mississippi River, Harmar and Clifford (2006) needed to divide the river into reaches with similar planform characteristics. They applied a statistical zonation algorithm to a data series based on lateral direction changes digitised from historic maps. The remainder of this chapter builds on the approach developed by Harmar and Clifford (2006; 2007), which was targeted on morphological and longer-term process realisations, and explores the potential for using statistical methods to define functional reach boundaries based on the concept that the reach characteristics of interest are internally homogenous and comparatively distinct with respect to reach-averaged sediment transport capacity.

5.5 Study site and data sequence: sediment transport capacity along the River Taff, South Wales

The data sequence used in this exercise is the predicted bed material transport capacity for the Mean Annual Flow (Q_{MAF}) along the main stem of the River Taff. The physiography of the Taff catchment is described in Section 7.3.1, but to summarise, it is a large, cobble-bed river in South Wales that flows south from the southern Brecon Beacons to its confluence with the Severn estuary in Cardiff (Figure 7.4). The Taff was selected as the study site because of the relatively comprehensive data availability throughout its catchment. This is explained in more detail in Section 7.3.1, but in summary, LiDAR data covering the entire River Taff was made available to this study and provision of such extensive LiDAR data is relatively rare for academic studies.

Predicted bed material transport capacity was selected as the test variable as it is the parameter of primary importance in the reach-based sediment balance model developed in this thesis. To generate a sequence of Q_{MAF} bed material transport capacity values along the Taff's main stem, the bed material transport relationship derived in Chapter Six was applied using channel slope, width and Q_{MAF} values calculated every 50m along the channel in the manner described in Section 6.6. The resultant data sequence is displayed in Figure 5.1.

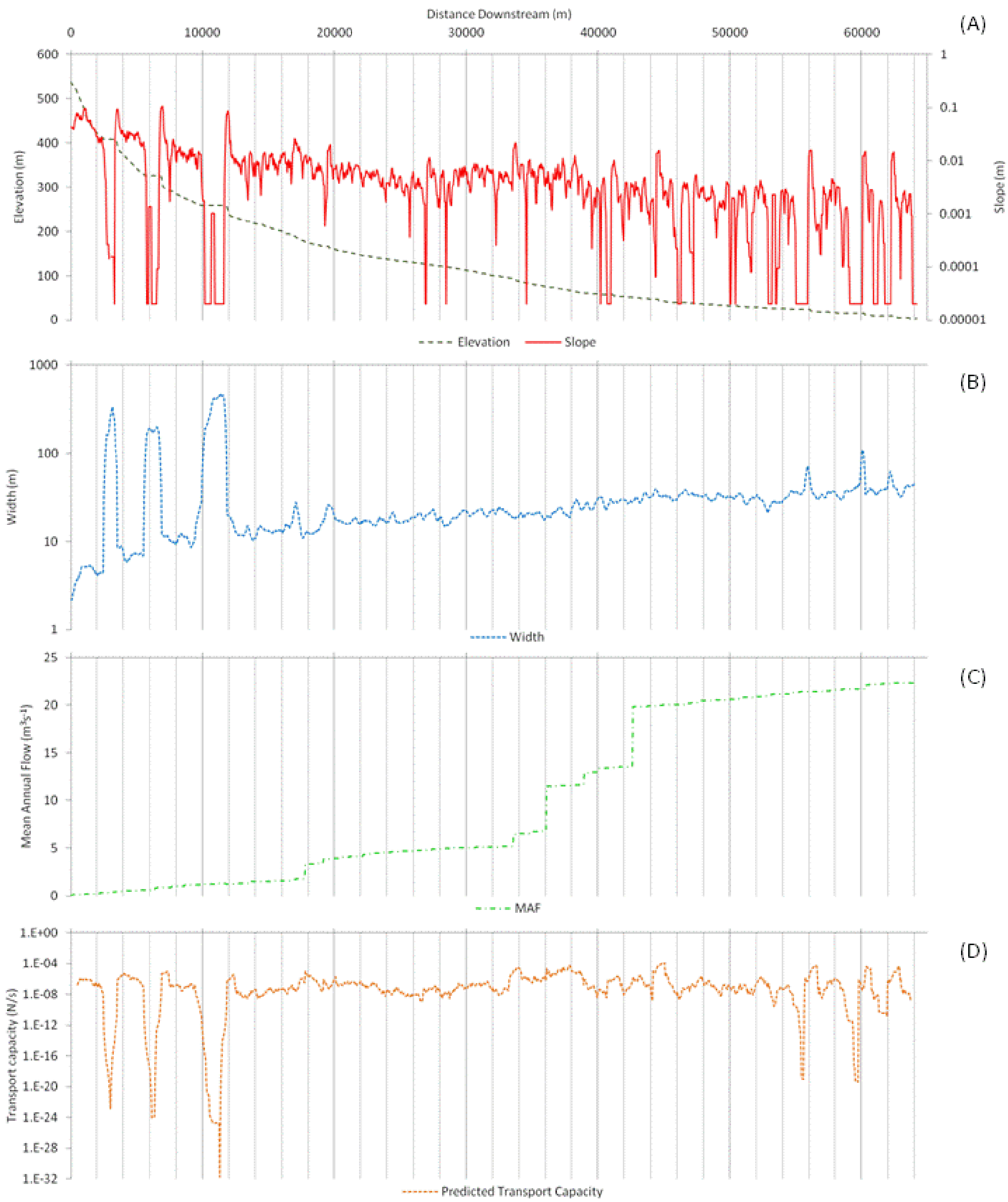


Figure 5.1 Data used for the River Taff main stem, values every 50m. (A) LiDAR channel elevation and slope values; (B) MasterMap width channel values; (C) Q_{MAF} values derived from catchment variables; (D) Q_{MAF} bed material transport capacity values.

5.6 Sequence zonation algorithms

"In recognising segments of sequential data which have like patterns, the geologist has no equal" (Hawkins and Merriam, 1973: 389). Various sub-disciplines within geology have had a long interest in dividing data sequences into relatively uniform segments that are distinctive from other, adjacent segments (Davis, 2002). For example, well-logs need to be sub-divided into relatively uniform sections that represent zones of consistent lithology, which correspond to stratigraphic units. Palaeontologists zone stratigraphic sequences on the basis of consistent abundance of microfossils. Airborne radiometric traverses may be sub-divided into zones that can be interpreted as belts of uniform rock composition or consistent mineralisation. Given their expertise in identifying relatively homogenous *stratigraphic* units, when attempting to identify relatively homogenous *river* units (reaches) it seems prudent to make use of techniques already proven in geology.

There are essentially two, contrasting approaches to zonation: 'local boundary hunting' and 'global zonation' (Davis, 2002). Both have been applied to data series that propagate in either time or space. Local boundary hunting procedures begin at one end of a sequence and progressively move to the other end, identifying abrupt changes in average values. Webster (1973) proposed one of the original versions of this type of procedure. His method involved a sampling 'window' of a specified width passing through each of the data points (Figure 5.2A). The window is divided in two, either side of the point in question. The technique involves comparing the difference between the points within the window that are located either side of the point in question, and then plotting these differences as the window moves through the data sequence (Figure 5.2B). The principle is that the difference between the two halves of the window will be largest at points where the most significant discontinuities in the data occur. Various statistics may be used to quantify the difference between the two halves of the window. One of the more commonly used statistics is the generalised distance (D^2)

$$D^2 = \frac{(\bar{X}_1 - \bar{X}_2)}{s_1^2 + s_2^2}$$

Equation 5.1

where $\bar{X}_1$ and $\bar{X}_2$ are the mean values from either side of the window, and s_1^2 and s_2^2 are the variance for the data either side of the window. The zone (reach) boundaries are then identified based on the points in the series with the maximum intra-window, generalised distances (Figure 5.2C).

Webster (1973) noted that the performance of this procedure varies with the width of the moving window (see Figure 5.2B and Figure 5.2C versus Figure 5.2D and Figure 5.2E). A wide window will average across small zones, subduing any erratic variability, but also masking any local variability. A narrow window is more sensitive, and will identify local changes in the sequence, but may also pick up noise in the original sequence.

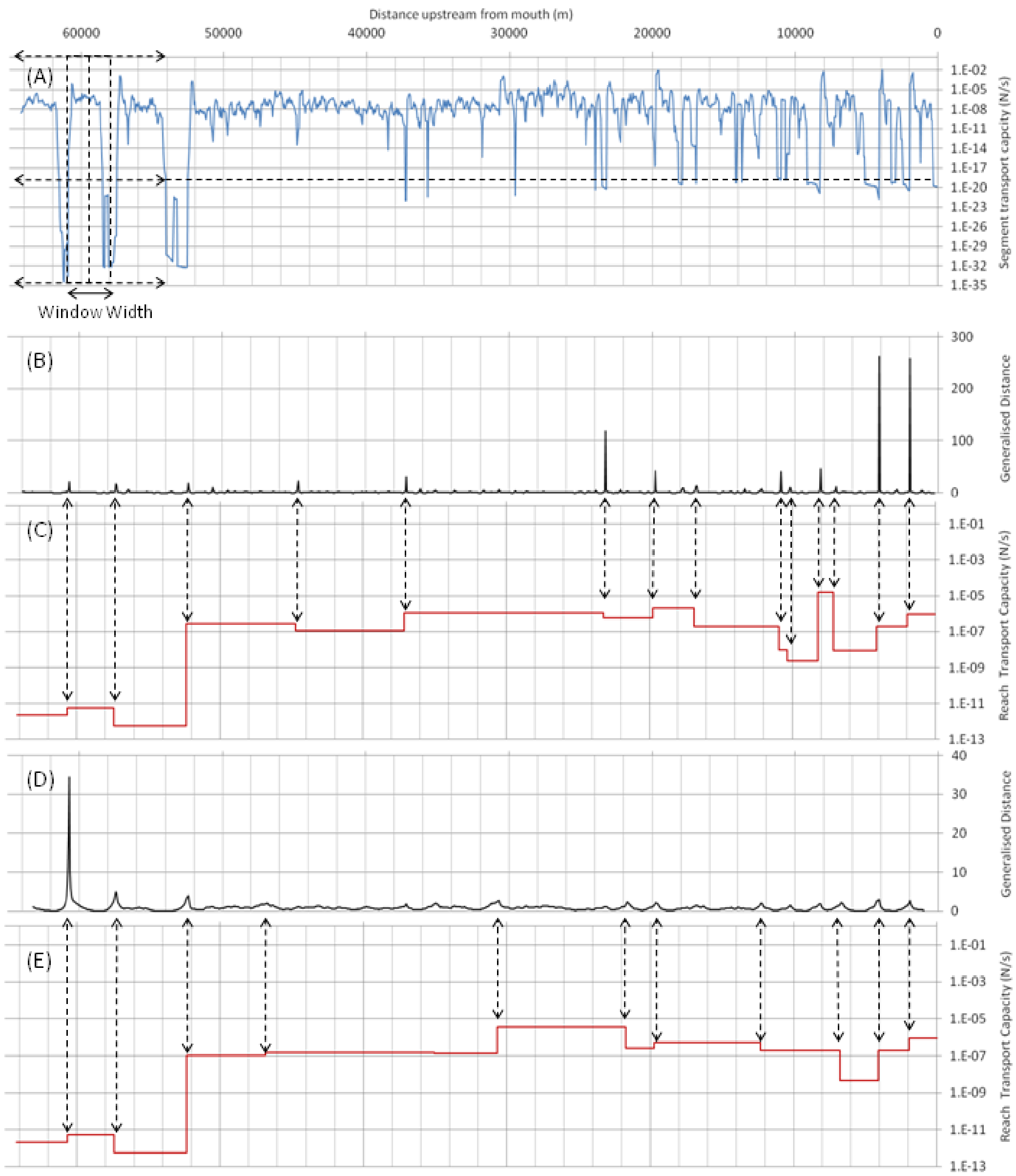


Figure 5.2 Demonstration of Webster's local boundary hunting method on a downstream sequence of bed material transport capacity for the main stem of the River Taff, South Wales. (A) Downstream plot of bed material transport capacity with sampling 'window'; (B) Downstream plot of generalised distances (D^2) in bed material transport capacity using a window width of 500m; (C) Downstream plot of reach-averaged bed material transport capacities using reach boundaries identified using a window width of 500m; (D) Downstream plot of generalised distances (D^2) in bed material transport capacity using a window width of 2km; (E) Downstream plot of reach-averaged bed material transport capacities using reach boundaries identified using a window width of 2km

By contrast, global zonation procedures break the sequence into segments which are as internally homogenous as possible and as distinct as possible from their adjacent segments. Unlike local boundary hunting methods, global procedures consider the entire sequence at once, rather than just the portion within a moving window (Davis, 2002). Three global zonation methods are considered here. The first was originally devised by Gill (1970) to analyse well-logs. This applies an iterative analysis of variance approach (Figure 5.3). The data sequence begins as one long zone (reach) and is temporarily divided into two zones, with the provisional partition falling between the first and second points in the sequence. At this stage, the sum of squares within the two temporary zones (SS_w) is calculated using

$$SS_w = \sum_{j=1}^{m} \sum_{i=1}^{n_j} (x_{ij} - \bar{X}_{*j})^2 / \sum_{j=1}^{m} n_j - m$$

Equation 5.2

where x_{ij} is the ith point within zone j, $\bar{X}_{*j}$ is the mean of the jth zone, n_j is the number of points in the jth zone, and m is the number of zones. Once this has been calculated, the partition between the two zones is moved along the sequence to successive positions and SS_w is calculated for every possible position of the partition. The partition which results in the lowest SS_w is selected as the first zonal boundary, forming two zones. The procedure then starts again, with the SS_w calculated for every possible position of the second partition, the minimum of which is used to divide the sequence into three zones. In this manner, Gill's (1970) method seeks to identify the zonation that minimises the variance within each zone (reach) and maximises the difference between the zones (reaches). The zonation procedure continues until the proportion of total variance explained by the zonation increases beyond a specified level.

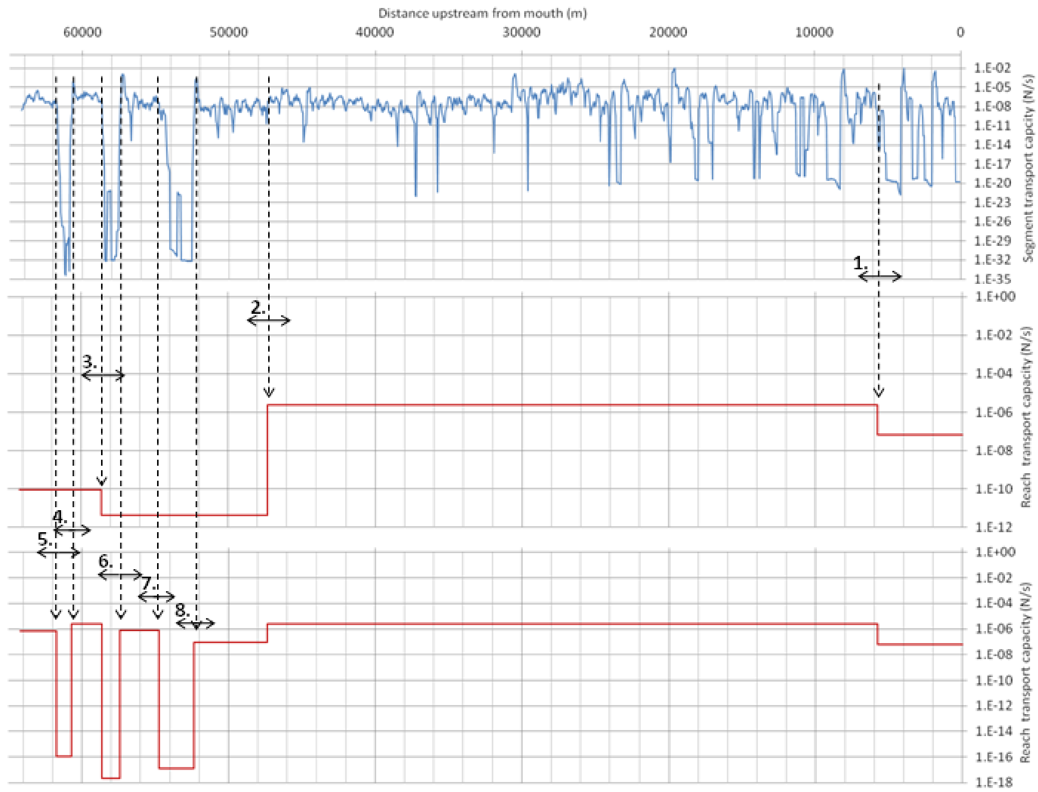


Figure 5.3 Demonstration of Gill's analysis-of-*variance global zonation method on a downstream sequence of bed material transport capacity for the main stem of the River Taff, South Wales. The numbers represent the order in which the partitions are made in the sequence.*

An alternative global zonation procedure was published by Hawkins and Merriam (1973). They found that, with a non-recursive procedure such as Gill's (1970), it is possible that the location chosen as the optimal partition at one stage in the iteration may no longer be optimal when looking to insert the next partition. As a solution, Hawkins and Merriam (1973) proposed a procedure that is similar to Gill's (1970), but which is recursive and takes advantage of Bellman's principle of optimality (Bellman, 1957) to ensure that the final set of zone boundaries is the best possible combination. Like Gill's (1970) method, Hawkins and Merriam's (1973) recursive procedure begins with the data sequence as one continuous zone. Then, whilst Gill's method makes its initial division based on the minimum SS_w from all potential locations of the first partition, Hawkins and Merriam's procedure calculates the SS_w value for every possible combination of the first *two* partitions. Once the combination of two partitions that results in the minimum SS_w

has been found, the procedure applies just the first of these partitions, dividing the sequence into two zones. To divide the sequence into three zones, the procedure considers which combination of the second and third partitions will result in the lowest SS_w. The process again continues until the proportion of total variance explained by the zonation increases beyond a user-specified level. Because of the recursive nature of Hawkins and Merriam's method, for a given number of zones, it is guaranteed to have the smallest within zone variance out of all of the possible combinations. However, this optimality is achieved at far higher computational cost.

Bohling *et al*. (1998) developed a zonation procedure to analyse well-logs based on hierarchical cluster analysis. This method differs from those of Gill (1970) and Hawkins and Merriam (1973) in that, rather than starting with the data sequence as one contiguous zone, it begins with the data sequence divided into as many zones (reaches) as there are values in the sequence. The first iteration involves calculating the difference between the value of every zone i and its neighbour, $i + 1$. The pair of zones with the smallest difference is combined into one zone. In the next iteration, this new composite zone is treated as a single object defined by the mean value of the points within it. The process continues, with more and more zones being progressively joined together, based on their similarity to each other (Figure 5.4). Unlike global zonation methods, which reduce SS_w with every iteration, the cluster method begins with zero within-zone variance (SS_w) and each iteration results in an increase in SS_w until the proportion of total variance explained by the zonation falls below a user-specified level.

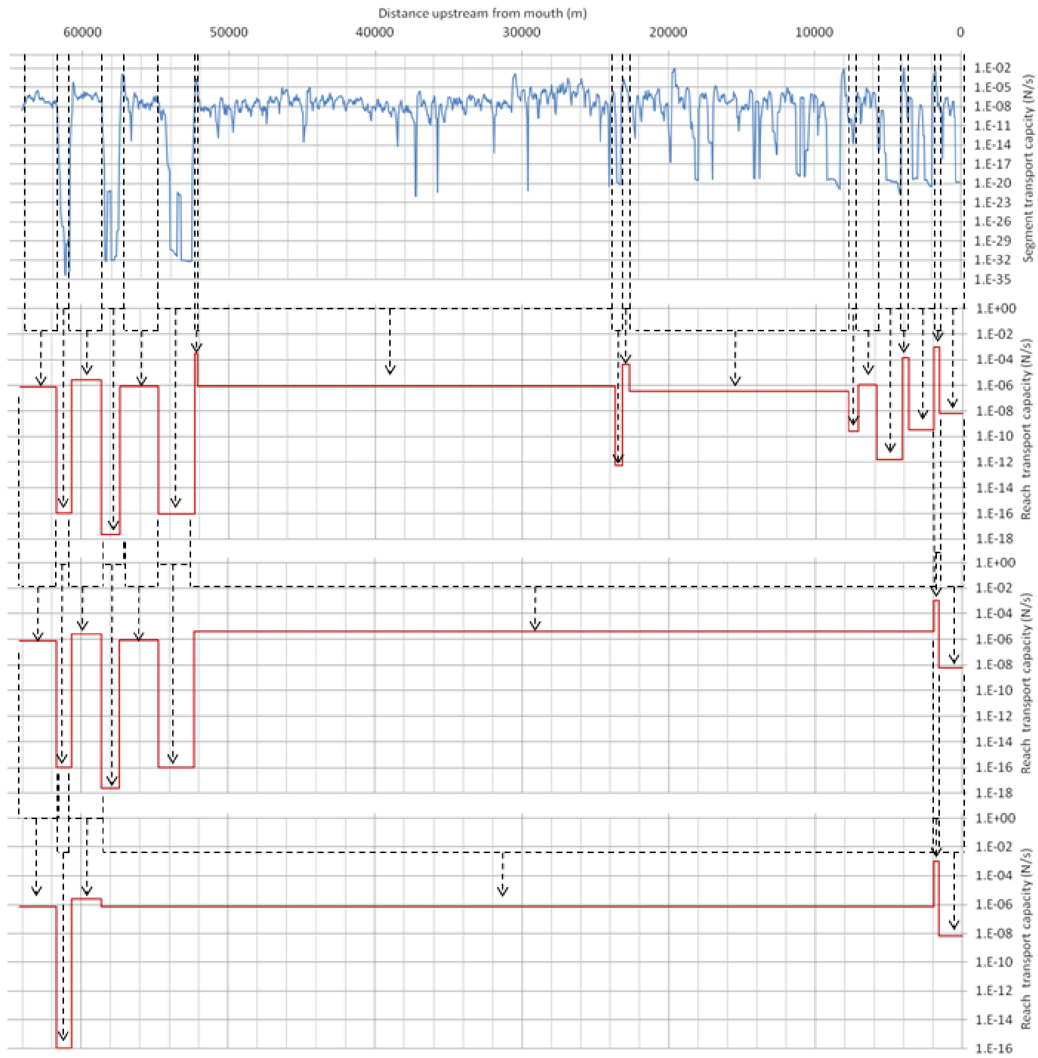


Figure 5.4 Demonstration of Bohling's hierarchical cluster global zonation method on a downstream sequence of bed material transport capacity for the main stem of the River Taff, South Wales

5.7 Evaluation of sequence zonation algorithms

All four of the sequence zonation algorithms described above were applied to the sequence of predicted bed material transport capacity data calculated for the River Taff. Figure 5.5 compares the ability of each algorithm to define internally homogenous and comparatively distinct reaches based on how the proportion of variability explained by the reach boundaries (R) increases with the number of reaches identified, where $R = SS_B/(SS_B + SS_W)$, SS_B is a measure of the variance of the reach means about the grand mean of the whole sequence ($\bar{\bar{X}}_{**}$)

$$SS_B = \sum_{j=1}^{m} (\bar{X}_{*j} - \bar{\bar{X}}_{**})/m - 1$$

Equation 5.3

and SS_W, j, m and $\bar{X}_{*j}$ are as defined in Equation 5.2. This assumes that the higher the proportion of variability explained by the reach boundaries for a given number of reaches, the more suited the zonation algorithm is to defining functional river reaches.

The three global zonation algorithms all performed better than Webster's local boundary hunting method. When dividing the initial sequence into reaches, all three versions of Webster's algorithm explain considerably less variation (lower *R*) than the methods of Gill, Hawkins and Merriam and Bohling. The main weakness of local boundary hunting procedures like Webster's (1973) is that they are concerned with finding local breaks in the sequence, with little reference to the importance of these breaks in the sequence as a whole. Therefore, they do not necessarily prioritise the break points that are of most importance in terms of minimising intra-reach and maximising inter-reach differences. Further, as identified by Davis (2002) and illustrated in both Figure 5.2 and Figure 5.5, the performance of local boundary hunting procedures is dependent on the width of the moving window, a variable for which the specification is somewhat arbitrary. This makes the effective application of a local boundary hunting method difficult without the detailed *a priori* knowledge necessary to inform the choice of an optimum window width. The three global zonation algorithms explain similar proportions of variation as the initial data sequence is divided into multiple reaches. However, after the sequence has been divided into approximately 25 reaches, the proportion of variance explained by Bohling's algorithm falls below that explained by the other methods.

A further, detailed comparison of the actual reach boundaries identified by the Gill and Bohling methods reveals an important difference in how they prioritise reach boundary placement. Figure 5.6 shows the reach extents identified by each of the algorithms for equivalent numbers of reach boundaries. Examination of this, and other zonations, by the two algorithms shows that the Bohling, clustering-based, method tends to identify boundaries at large, local inconsistencies in the data sequence. This is because it is at these points that the clustering method avoids grouping points on either side into reaches. By contrast, Gill's method identifies boundaries based on broader-scale differences in the data sequence, rather than individual local/temporary inconsistencies. This means that individual large local variations are tolerated within a reach, as long as the total variation within all reaches is kept to a minimum. This is preferable, as large local changes, such as those associated with morphological steps in a step-pool reach, or weirs in a low gradient reach with a number of in-stream structures, do not necessarily constitute functional reach boundaries when considered in the context of the entire catchment. This also means that the analysis of variance approaches are less sensitive to local discrepancies in data.

Based on these results, the analysis of variance approaches adopted by Gill (1970) and Hawkins and Merriam (1973) seem well suited to the identification of river reach boundaries. Not only do they statistically minimise within-reach variation while maximising between reach differences, but they also identify reach boundaries based on broad-scale, functional changes because they are less influenced by local inconsistencies in the data sequence.

Unsurprisingly, given their related structure, the Gill (1970) and Hawkins and Merriam (1973) methods explain almost exactly the same proportion of variation for any specified number of reach boundaries. In practice, the locations of reach boundaries identified by these two algorithms are also nearly identical. As mentioned earlier, the recursive nature of Hawkins and Merriam's method comes at a high computational cost, especially when dealing with a large number of data points. In this investigation, it took over a week for a standard modern desktop computer (Dual Core 2Ghz processor, 2GB RAM) to place 100 reach boundaries in the Taff data sequence. As, at least in this application, there is little difference between the reach boundaries identified by the Gill and Hawkins and Merriam methods, the faster, non-recursive algorithm was selected.

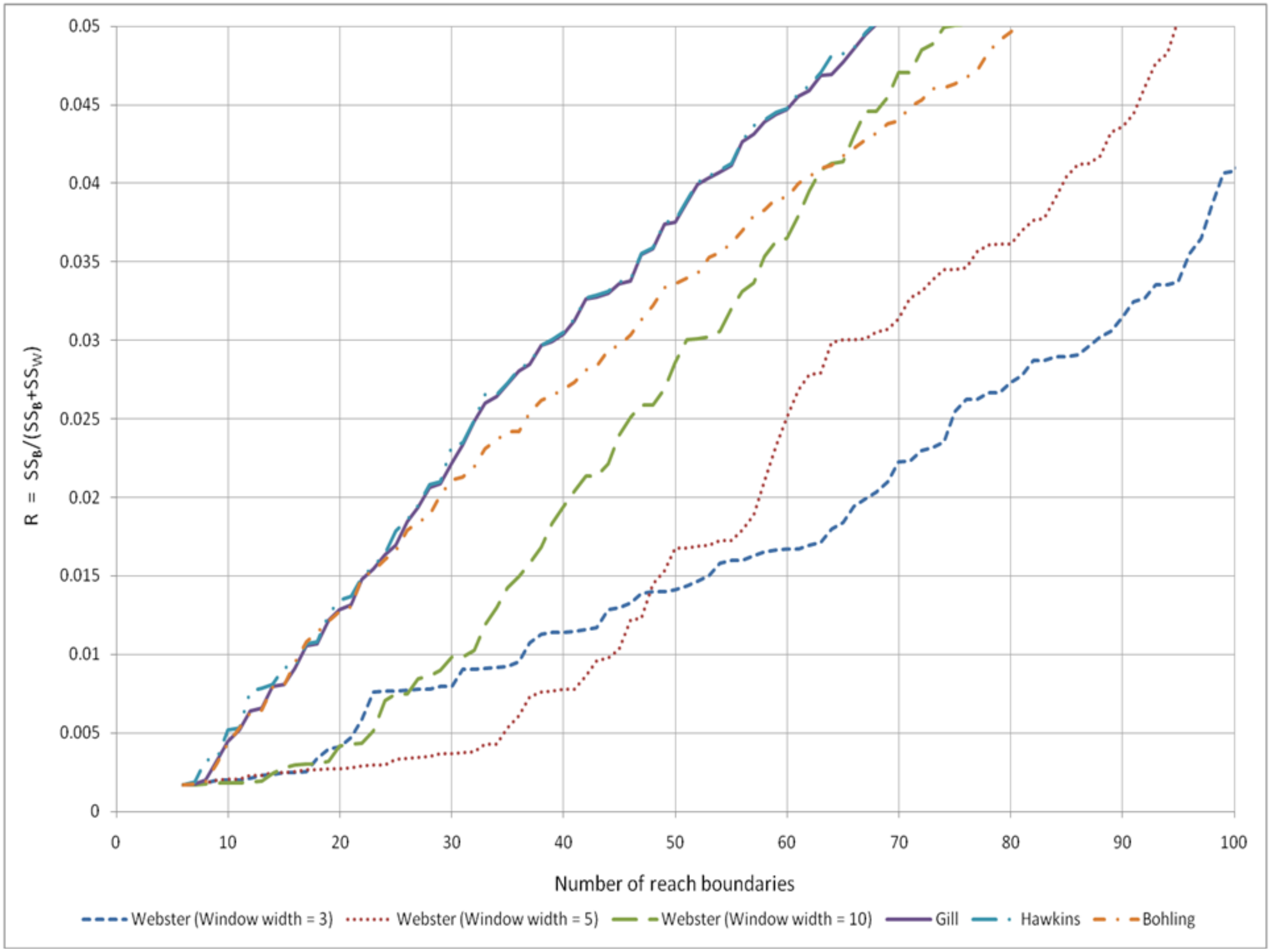


Figure 5.5 Change in R (proportion of variability explained by reach boundaries) with the number of reach boundaries identified for each of the zonation algorithms considered.

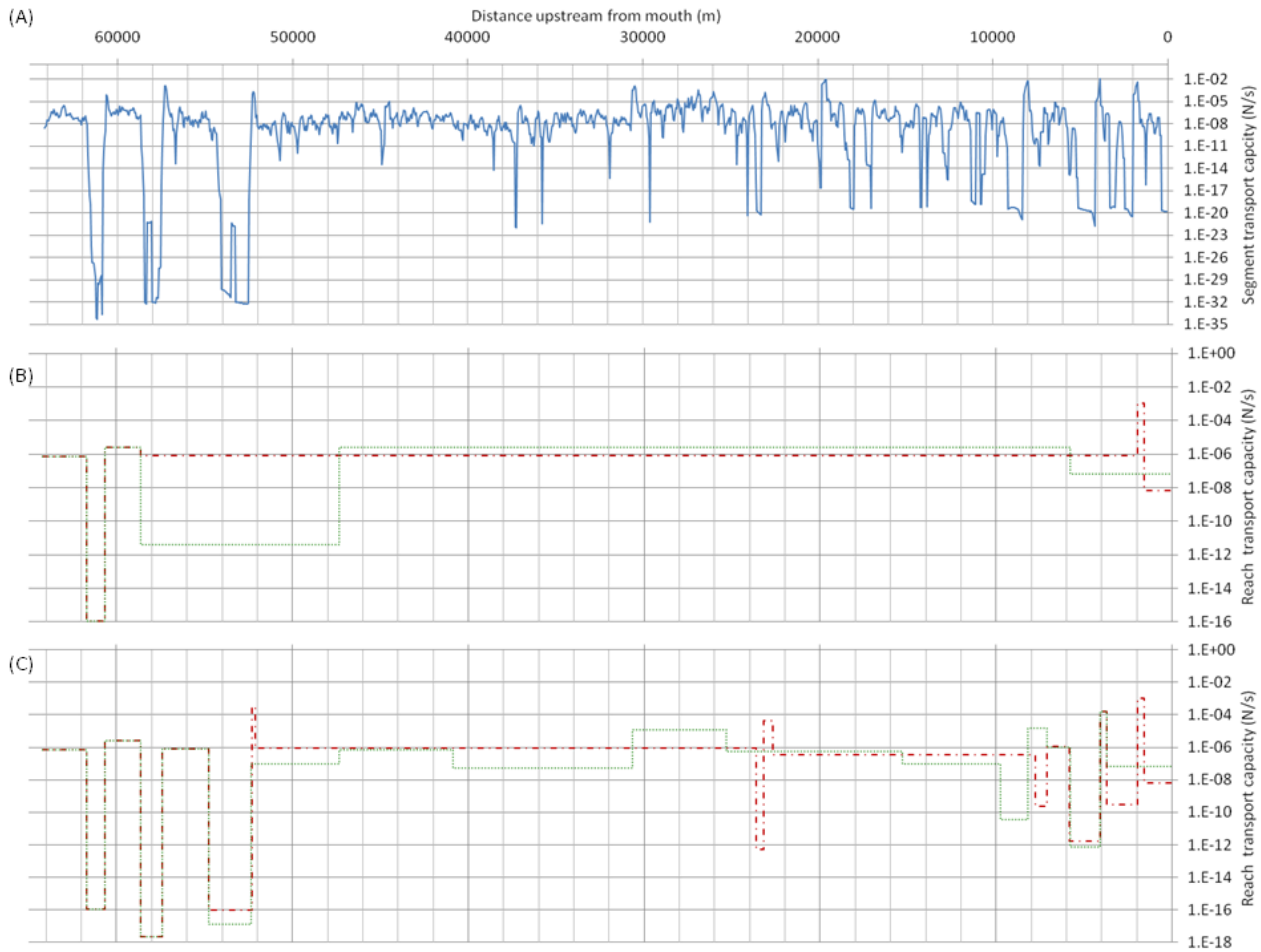


Figure 5.6 Comparison of reach boundaries selected by the Gill (solid green lines) and Bohling (red dashed lines) zonation algorithms along the River Taff main stem. (A) Downstream plot of bed material transport capacity; (B) Reaches identified by the two zonation algorithms after 5 boundaries; (C) identified by the two zonation algorithms after 17 boundaries.

5.8 Incorporating a functional reach boundary hunting algorithm into a reach-based sediment balance approach

It is recognised that the testing of the boundary hunting algorithms described above cannot be considered complete. The above testing has just shown that Gill's (1970) zonation algorithm is the most suited to identifying reach boundaries within the main stem of the River Taff that statistically minimise within-reach variation in sediment transport capacity while maximising between reach differences. This testing is limited in that:

i) It is based on the assumption that minimisation of within-reach variability in sediment transport capacity is equivalent to identification of functional reach boundaries; and

ii) The main stem of the Taff is representative of all rivers in regard to its division into functional reaches.

In order to fully test the suitability of Gill's (1970) zonation algorithm for defining functional reach boundaries it is therefore necessary to test it, and the other zonation algorithms, against expertly identified functional reach boundaries within a range of river types. However, this is not attempted within the scope of this study and therefore this additional testing of zonation algorithms is recommended as an area for future research. The testing described in this chapter is therefore considered sufficient to warrant the inclusion of Gill's (1970) zonation algorithm into the new reach-based sediment balance model developed in this study. In order to ensure that the zonation algorithm produces reaches that are useful for application within the model, a number of additional amendments were made to the zonation process. These are summarised in the remainder of this section.

As described above, within zonation algorithms the number of reaches that the data sequence is divided into is controlled by the proportion of the variability in the sequence (R) explained by the reach boundaries. Therefore, selecting different values for R will alter the number and length of reaches delineated by the zonation algorithm. It was decided that R should be a user-defined parameter in the new approach, but that its default setting should be 0.01 (explanation of 1% of the total variability in the predicted transport capacity data sequence).

Due to the representation of the entire catchment network in the new reach-based sediment balance model it is also necessary to ensure that a new reach begins at every confluence so that the inputs to the reach downstream of a confluence include both the outputs of the reach upstream on the main stem, and the outputs of the reach upstream on the tributary. To achieve this, the zonation code was modified so that boundaries at each confluence in the network are imposed before any new reach boundaries are found.

During testing, it was found that more extreme values of sediment transport capacity impacted more strongly on the proportion of variability explained by the reach boundaries (R). Therefore, to improve the consistency of performance of the zonation algorithm across a range of different catchments, the data sequence used in the zonation procedure was converted from the raw predicted transport capacity series into a ranked series where each point in the sequence was given a rank number depending on where that value fell in relation to all the other values in the series. This was found to improve the performance across a range of different catchments, while maintaining consistency in the process underpinning the reach boundary hunting process.

Finally, it was also observed that, where a data sequence included a section with a significant and progressive increase or decrease, more than one reach boundary may be identified within that increasing or decreasing sequence. This tends to mask the overall difference in transport capacity between the start and end of the sequence, since the total difference is split over multiple reach boundaries. To avoid this problem, the zonation algorithm was modified so that the proximity of successively increasing or decreasing reach boundaries was considered in blocks of at least five segments.

5.9 Alternative applications for sequence zonation algorithms

5.9.1 Broad-scale reach habitat quality restoration prioritisation – River Frome, Somerset

Driven in part by the European Water Framework Directive (Harper and Ferguson, 1995; Newson, 2002; Raven *et al.*, 2002; Eyquem, 2007; Orr *et al.*, 2008), there has been a recent increase in recognition of the importance of conserving or restoring river habitat as part of modern river management. To achieve 'good ecological status' throughout a catchment, river scientists and managers need to identify, and prioritise, those parts of a river with the highest potential for habitat restoration. The most widely available data source that gives information on river habitat quality is the Environment Agency's River Habitat Survey (RHS – see Section 3.2.2).

The Habitat Quality Assessment (HQA) scoring system is a broad measure of the diversity and 'naturalness' of physical (habitat) structure in the channel and river corridor based on data contained within the RHS. The HQA score of a site is determined by the presence and extent of habitat features of known wildlife interest recorded during the field survey. Rare features such as waterfalls more than 5m high and extensive fallen trees score additional points in the HQA. Point scoring for the HQA system is based on a consensus of informed professional judgment. It is subjective, but provides the necessary consistency for comparisons. Features that score within the HQA are consistent with those included in the 'System for Evaluating Rivers for Conservation' (SERCON), for which a panel of ecological experts identified the attributes of most value to riverine wildlife (Boon *et al.*, 1997).

Raven *et al.* (1998b) warn that comparison of HQA scores for different river types is not meaningful, but by comparing the HQA scores between reaches in the same catchment, it is possible to identify whether a reach provides relatively high or low quality habitat. This information can be used by river managers and conservationists to identify locations within a catchment where river habitat restoration efforts would have the best chance of success. However, as demonstrated in Figure 5.7A, which shows the HQA scores for a series of RHS reaches along the River Frome in Dorset, locations of high and low quality habitat are not clearly defined. This is because the boundaries of the operationally defined, uniform 500m RHS reaches are not aligned with the forms and processes that influence habitat quality but are, instead selected arbitrarily. This means that variations in river habitat quality at a spatial scale finer than 500m are not discernible in the RHS-based HQA scores. Neither is the spatial distribution of habitat quality at a spatial scale coarser than 500m initially apparent from HQA scores based on operationally defined, 500m reaches. As the RHS reach boundaries and the forms and processes of interest do not necessarily align, difficulty arises in identifying the location and spatial extent of the sections of channel over which habitat quality is low. Therefore, the reaches of channel where management action has the highest priority cannot be discerned.

Little can be done to identify any functional reaches that may occur at a scale smaller than the 500m RHS reach length, but an automatic reach delineation algorithm could be applied to a longitudinal sequence of HQA scores to identify functional reaches that are associated with broader-scale variation in river habitat quality. Figure 5.7B demonstrates how the sequence of HQA scores in Figure 5.7A can be automatically discretised into a series of functional reaches using Gill's (1970) analysis of variance global boundary hunting algorithm. The detection of reaches based on statistically defined boundaries in the HQA data sequence, rather than on an arbitrarily selected uniform length of channel, not only identifies changes in habitat quality but also reveals a clear spatial structure to the data (Figure 5.7C). These outputs would, therefore, be useful to river managers seeking to prioritise parts of a catchment for river habitat restoration. Further, from a researcher's perspective, the broad-scale variations in habitat quality revealed in Figure 5.7C could also be linked to other catchment variables to identify broad-scale drivers of habitat quality status.

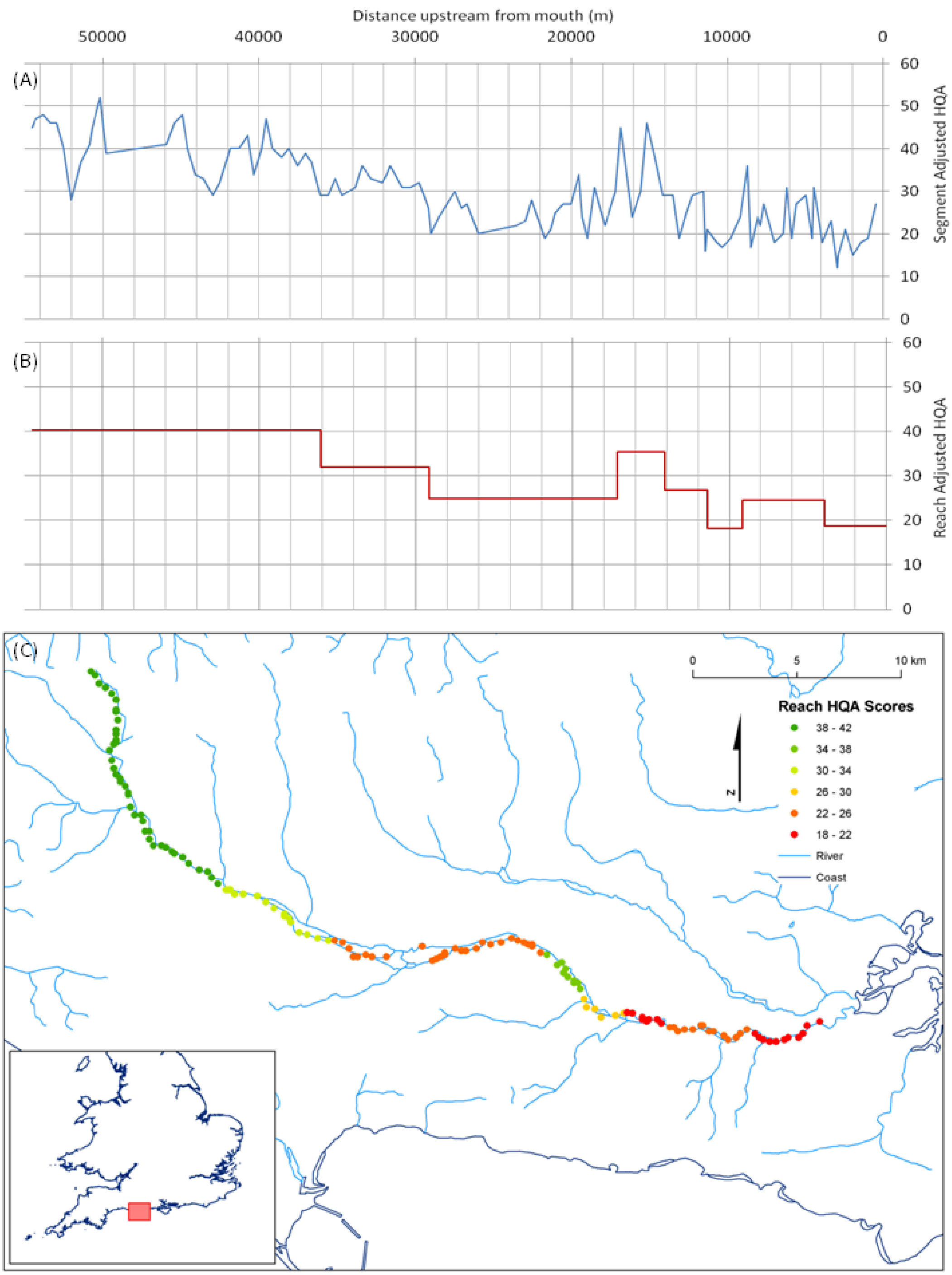


Figure 5.7 Identification of functional reaches based on RHS Habitat Quality Assessment (HQA) scores on the River Frome, Dorset. (A) Downstream plot of HQA scores for all RHS site. (B) Downstream plot of average HQA scores for functional reaches. (C) Map showing spatial distribution of average HQA scores for functional reaches.

5.9.2 Spatial framework for integrated catchment management

It has been demonstrated here that automatic functional reach delineation can be applied within multiple disciplines of river research and management: Gill's (1970) zonation algorithm has not only been successfully applied to a sequence of predicted sediment transport capacity values for the main stem of the River Taff, but it has also been used to split a sequence of Habitat Quality Assessment scores along the River Frome in Somerset into meaningful reaches. In practice, this type of automatic functional reach identification procedure could be applied to numerous other aspects of river research and management. For example, investigations into how water quality varies spatially throughout a river network could use an automatic functional reach delineation procedure to a longitudinal series of Water Quality Index (WQI) values. The resultant, discretised reaches and their reach-averaged WQI values could help simplify downstream spatial variation and emphasise meaningful spatial structure in the data. Similarly, the procedure could be applied to sequences of bed material size, invertebrate richness, channel width, or pollutant concentration.

It has been argued here that global zonation procedures are of practical utility in many aspects of river research and management due to their capability for identifying functional river reaches based on univariate data series. However, a potentially more important application remains unexplored. Since the mid-1990s, the tradition of reporting on different aspects of rivers in isolation has been superseded by a multidisciplinary approach based on the principles of integrated river basin management (Harper and Ferguson, 1995). Raven *et al*. (1998a) identified that, in order to facilitate integrated approaches, all management 'viewpoints' need to be based upon a consistent yet flexible approach.

Data sequence zonation algorithms can be applied not only to univariate data (as demonstrated herein), but also multivariate data sequences (Davis, 2002). To facilitate this, the data sequences must be standardised so that they each have an equal influence on the zonation, and the resultant boundaries represent divisions that are dominant across all of the contributing variables. There is, consequently, the potential to apply an algorithm similar to that proposed by Gill (1970), across several data sequences that each represent a variable of interest in the context of integrated catchment management. For example, functional reach boundaries could be identified based on sequences representing sediment transport capacity, habitat quality, water quality, invertebrate abundance, and low flow discharge. The resultant, combined functional reaches would then provide a consistent spatial framework within which all of these aspects of river management could be considered in an integrated approach.

Further research into advancing the utility of automatic reach boundary hunting algorithms is recommended, first with the aim developing the optimum statistical procedure for reach designation and, second and more importantly, to explore how this type of technique can be deployed in developing practical data handling strategies needed to underpin integrated catchment management.

Following the progress made in Chapters Four and Five, the remaining issue requiring resolution in the formation of a new reach-based sediment balance approach is the development of a suitable sediment transport relationship. This will be the focus of Chapter Six.

Chapter Six: Predicting reach coarse sediment transport capacity – development of a general bed material transport relationship

6.1 Introduction

Coarse sediment transport drives the relationship between the hydraulics of flow and the characteristics of the bed materials that control river-channel morphology. Consequently, as outlined in Section 2.5, knowledge of coarse sediment transport is necessary to inform the understanding of channel change. Also, knowledge of coarse sediment transport is essential to river managers, as they need it to inform decision making when addressing problems in the fluvial environment and attempting to achieve multiple, functional objectives.

As identified in Section 4.6, due to the substantial expense involved in collecting bed-load transport data, sediment transport formulae are widely applied as predictive tools. However, there remains considerable difficulty in consistently applying any of these formulae with a level of accuracy that is deemed acceptable. This chapter explores the reasons behind this apparent failure, arguing that they result as much from the unreasonable expectations of those deriving and evaluating sediment transport formulae as they do from our limited ability to represent the physical processes involved in the bed-load transport. Based on this line of argument, this chapter describes the derivation of a new general expression for the rate of coarse sediment transport by a stream. This general expression is based upon the analysis of over 120 separate bed-load transport datasets. These datasets are examined to identify the hydraulic parameter that is correlated most strongly with measured bed-load transport rates. The datasets are subsequently modified, first, to account for supply-limitations and, second, to represent the transport of the observed bed surface material, rather than the entire bed-load. The resulting transport-limited, *bed surface material* transport datasets are then used to derive a relationship between the selected hydraulic parameter and the bed surface material transport rate. The nature of this new relationship is described and its implications discussed before the practical procedures necessary to apply it to British rivers at the catchment-scale are described.

6.2 'Failures' to adequately represent bed-load transport rates

The mechanics of sediment transport is so complex that it is extremely unlikely that a full understanding will ever be obtained… a 'universal sediment transport equation' is not and may never be available.

(Simons and Senturk, 1992: 695)

This quote characterises the state of exasperation that many sediment transport scientists and engineers have reached in their attempts to consistently represent sediment transport rates to a level of precision and accuracy that is deemed acceptable. In the 130 years since du Boys (1879) made the first attempt by modern scientists to quantify the relationship between hydraulic variables, sedimentological variables and sediment transport rate, a succession of sediment transport scientists have followed his lead, each attempting to resolve the inconsistencies and inaccuracies of those that preceded them. Yet, despite the substantial investment into this sphere of research, no existing sediment transport formula has yet been found to consistently predict transport rates to an acceptable level of accuracy (Gomez and Church, 1989; Bravo-Espinosa *et al.*, 2003; Barry *et al.*, 2004). There are two key factors responsible for this. The first factor relates to the manner in which sediment transport formulae are derived together with a paucity of reliable empirical data. The second factor is concerned with the over ambitious and, in some applications, potentially unnecessary, levels of accuracy and precision expected of transport formulae.

The majority of studies into sediment transport rates involve construction of a formal relation between selected hydraulic and sedimentological parameters and the sediment transport rate, either through empirical measurements made in field and flume conditions or based on theoretical principles. In either case, the resultant relationship is generally tested and calibrated using a limited body of empirical data. Gomez and Church (1989) highlighted adherence to this common approach as being a driver behind the inability of sediment transport equations to meet expected standards of accuracy, which had led to the *"proliferation rather than the consolidation of bed-load transport formulae"* (1989: 1161). The outcome is that over a century of research has not resulted in a single, general sediment transport formula, but multiple formulae, each of which can adequately predict sediment transport rates, but only under conditions similar to those from which they were derived. It is therefore unsurprising that Gomez and Church (1989) found none of these formulae performed well across a wide range of hydraulic and sedimentological conditions.

The large number and variety of sediment transport relations is, perhaps, to be expected given the diversity and complexity of transport conditions that exist within natural systems. Early attempts at deriving transport relations were justifiably based around simple representations of the fluvial system: unimodal sediments of regular shape under controlled flow conditions. The resulting equations reflected these simple representations of the nature of the hydraulic and sedimentological conditions. But in natural systems, a large number of variables influence the transport of bed material. The sediment size, density of material, grain shape, breadth of grain size distribution, modality of grain size distribution, degree of packing, presence of vegetation, level of imbrication, bedform roughness, presence of fines, upstream sediment supply, and irregularity of flow over the bed can all influence transport rates (Gomez, 1991; Simons and Senturk, 1992; Wilcock and Crowe, 2003). Because each of these factors varies between the empirical datasets that have been used to develop and calibrate sediment transport formulae, each formula is specific to those conditions.

Recent attempts to predict bed-load transport rates have begun to account for more of the factors identified as influencing transport rates. For example, Wilcock and Crowe (2003) present a multiple size fraction bed-load transport model that not only incorporates a hiding function to account for the influence of hiding and protrusion, but also accounts for the nonlinear effect of fines content on gravel transport rate. The addition of variables representing these effects into the transport relationship increases the breadth of sedimentological conditions across which the formula can be applied. It is therefore possible that, through a similar process, a model for bed-load transport could be derived that accounts for all the factors known to influence transport rates. However, it is clear that there is much work still to be done. Further, the complexity of any expression that incorporates the effects of all influencing factors would limit its application to those rare situations where the end-user has detailed knowledge of all aspects of the fluvial and sedimentological system. Richards (2004: 112) reached a similar conclusion, identifying that theoretical sediment transport equations *"can rarely accommodate all the potential variables without becoming practically unworkable".*

The conventional approach described above, whereby transport relations were derived and tested using simplified representations of the fluvial system, did not only result in expressions that were unsuited to application in natural systems. It also raised the expectations of sediment transport researchers in terms of the level of accuracy that should be expected from sediment transport formulae. Failure to produce sediment transport equations that achieve the expected levels of accuracy is not solely due to their inability to properly represent sediment transport processes, but is also a result of the setting of targets and benchmarks that were overly ambitious and unattainable. It is argued here that expectations concerning attainable levels of accuracy have been too optimistic in a number of ways, including: in comparison to the accuracy required for many applications of sediment transport formulae; in consideration of the practical constraints on many applications of sediment transport formulae; and in comparison to the accuracy of the field measurements of sediment transport used to validate formulae.

The root cause of the setting of unrealistic targets for accuracy may be traced back to the context within which the majority of early sediment transport studies were performed. For instance, because Yang (1972) was able to achieve correlation coefficients of 0.99 when predicting the sediment transport rates observed within Gilbert's (1914) flume studies, it seems reasonable that his equation should also be capable of predicting transport rates to comparable levels of accuracy in rivers. An engineering-based culture within sediment transport research is considered to have contributed to this reasoning and it is largely because river engineers have been unable to consistently replicate the high levels of accuracy achieved in the laboratory when working in natural systems that they have become so frustrated with the 'failure' of their efforts. This is reflected by Gomez (1991: 90), who identified that it is the *"reluctance to acknowledge that bedload transport is inherently unstable, rather than a lack of fundamental knowledge per se…"*, that has limited progress.

The level of accuracy actually required by a sediment transport formulae might, as an alternative, be judged against the needs of its application rather than the precision that can be achieved in a controlled laboratory environment. Experience shows that, in many project-related applications, predictions of absolute, instantaneous rates need to be little more than indicative. Typical applications of sediment transport formulae include: the design of river restoration channels to balance transport capacity with supply of sediment from upstream reaches (Soar and Thorne, 2001; Shields *et al.*, 2003); estimation of sediment flux within reduced complexity models of fluvial systems (Coulthard, 2001; Nicholas, 2005) and the design of channel maintenance flows downstream of reservoirs (Schmidt and Potyondy, 2004). These types of application generally involve the integration of predicted transport rates over time and space, negating the need for accurate estimates of sediment mass transported at a specific point in time and space. Indeed, some applications requiring sediment transport estimates are not explicitly dependent on absolute estimates but instead, simply require relative values in comparison with upstream supply reaches (Soar and Thorne, 2001). In particular, reach-based sediment balance models are not concerned with accurate predictions of the absolute rate of erosion or deposition in a reach, but instead require relative predictions of sediment transport rates in adjacent reaches in order to compute an annual sediment balance.

The applicability and utility of sediment transport formulae are also frequently limited by practical issues. As described earlier, in order to attempt to predict sediment transport rates it is necessary to account for a large number of influencing variables. Difficulty arises when applying highly parameterised formulae because of the expense involved in quantifying all of the necessary variables. It is impractical to expect practitioners interested in predicting transport rates at multiple locations across whole catchments to use sediment transport equations that require complete particle size distributions, or values describing in detail the type and density of in-channel vegetation. In fact, in some situations, it is impractical to expect that data defining channel flow properties such as depth and velocity are available because of difficulties in measuring and properly representing channel roughness (Ferguson, 2005).

It therefore seems appropriate to take a new initiative aimed at developing a general, coarse sediment transport relationship suitable for use in applications that do not require particularly high levels of accuracy. The remainder of this chapter looks to derive, describe and evaluate such a relationship, as well as consider how it can be calculated throughout British river catchments.

6.3 Data and methods

6.3.1 Bed-load transport database

Hydraulic, sedimentological and sediment transport measurements were obtained for all known and available bed-load transport studies. These included data from 133 different river and flume datasets described in a selection of agency reports, academic journal papers, theses, and files provided by researchers through personal communication (Yang, 1979; Gomez and Church, 1988; Bravo-Espinosa, 1999; Wilcock *et al.*, 2001; King *et al.*, 2004; Ryan *et al.*, 2005). The sources are summarised in Table 6.1 and the collated dataset is included in Appendix A. The resultant dataset is designed to be as extensive and inclusive as possible, spanning a wide range of flow dimensions, experimental designs, channel gradients and bed material sizes. The integrity of the data was accepted as being as described in the source publication unless obvious errors were discovered, in which case the data were rejected.

*Table 6.1 Summary of all bed-load transport datasets used within analysis (*Values unavailable)*

Data Source	Data Type	Dataset	N	Surface material D_{50} (m)	Width (m)	Depth (m)	Average Velocity (m^1s^{-1})	Slope (m / m)	Transport rate per unit width ($kg^1m^{-1}s^{-1}$)
Bravo-Espinosa, 1999	Field	Clearwater River at Spalding, Idaho	78	0.0740	125 - 137.9	3.29 - 4.58	0.69 - 1.88	0.00009 - 0.00030	0.00008 - 0.03261
		Snake River near Anatone, Washington	63	0.0540	155 - 180.4	3.26 - 4.68	1.51 - 2.44	0.00056 - 0.00092	0.00006 - 0.08406
		East Fork River, Wyoming	118	0.0450	14.6	0.28 - 1.03	0.61 - 1.01	0.00070	0.00033 - 0.05374
		Oak Creek near Corvallis, Oregon	33	0.0540	3.7	0.20 - 0.31	0.75 - 1.25	0.00970 - 0.00994	0.00001 - 0.02343
		Chippewa River at Durand, Wisconsin	25	-*	153 - 209	0.61 - 1.49	0.50 - 0.79	0.00029 - 0.00032	0.00386 - 0.03804
		Chippewa River at Pepin, Wisconsin	18	-*	171 - 239.8	0.75 - 1.15	0.45 - 0.65	0.00017 - 0.00034	0.00684 - 0.02763
		Horse Creek near Westcreek, Colorado	21	-*	6.9 - 7.7	0.29 - 0.41	0.54 - 0.95	0.00390	0.00106 - 0.10371
		La Garita Creek, Colorado	25	-*	4.6 - 5.3	0.19 - 0.31	0.34 - 0.64	0.01349	0.00010 - 0.00188
		N Fork South Platte River at Buffalo, Col.	20	-*	13 - 14.1	0.59 - 0.68	0.71 - 1.05	0.01070	0.00092 - 0.03774
		N Fork Toutle River at Kid Valley, Wash.	10	-*	18 - 38.6	0.39 - 0.72	1.20 - 1.96	0.00320 - 0.00420	0.04778 - 1.92686
		Toutle River at Tower Road, Wash.	31	-*	17.5 - 53.2	0.37 - 0.95	0.79 - 1.81	0.00107 - 0.00240	0.03371 - 1.02706
		Williams Fork near Leal, Colorado	16	-*	17 - 17.8	0.26 - 0.46	0.90 - 1.25	0.00580	0.00076 - 0.00484
		Wiscosin River at Muscoda, Wisc.	19	0.0006	219 - 294.7	0.71 - 1.41	0.47 - 0.68	0.00020 - 0.00031	0.00479 - 0.03393
		Yampa River at Deerlodge Park, Col.	29	-*	69 - 90.1	0.63 - 2.30	0.56 - 1.09	0.00047 - 0.00064	0.00812 - 0.13381
Gomez and Church, 1989	Field	Tanana River, Alaska	14	-*	107 - 333.4	1.81 - 2.38	1.30 - 1.66	0.00047 - 0.00052	0.03270 - 0.10660
		Elbow River, Alberta	19	0.0760	38.7 - 43.5	0.63 - 0.75	1.62 - 2.04	0.00745	0.03850 - 0.42159
	Flume	Ikeda - Uni of Tsukuba	17	0.0065	4	0.08 - 0.19	0.99 - 1.28	0.00228 - 0.00494	0.00030 - 0.19860
		Johnson - IHR, Uni of Iowa: 1	44	0.0044	0.8	0.03 - 0.07	0.57 - 0.71	0.00175 - 0.00544	0.00005 - 0.00457
		Johnson - IHR, Uni of Iowa: 2	60	0.0034	0.8	0.02 - 0.07	0.49 - 0.62	0.00125 - 0.00459	0.00004 - 0.00481
		Johnson - IHR, Uni of Iowa: 3	55	0.0023	0.8	0.02 - 0.06	0.43 - 0.55	0.00155 - 0.00423	0.00004 - 0.00600
		Johnson - IHR, Uni of Iowa: 4	47	0.0014	0.8	0.01 - 0.04	0.29 - 0.46	0.00135 - 0.00424	0.00005 - 0.00656
		Johnson - IHR, Uni of Iowa: 5	41	0.0036	0.8	0.03 - 0.06	0.53 - 0.64	0.00180 - 0.00577	0.00005 - 0.00358
		Johnson - IHR, Uni of Iowa: 6	46	0.0018	0.8	0.01 - 0.05	0.36 - 0.47	0.00165 - 0.00446	0.00004 - 0.00553
		Meyer-Peter & Muller – 1	34	0.0287	2	0.34 - 0.68	1.80 - 2.27	0.00317 - 0.00790	0.01300 - 1.30444

Data Source	Data Type	Dataset	N	Surface material D_{50} (m)	Width (m)	Depth (m)	Average Velocity (m^1s^{-1})	Slope (m / m)	Transport rate per unit width ($kg^1m^{-1}s^{-1}$)
		Meyer-Peter & Muller – 2	17	0.0015	2	0.06 - 0.15	0.63 - 0.74	0.00225 - 0.00250	0.00450 - 0.06935
		Meyer-Peter & Muller – 3	7	0.0037	2	0.07 - 0.09	0.74 - 0.96	0.00801 - 0.00813	0.05900 - 0.24057
		Paintal - Uni of Minnesota: 1	13	0.0222	0.9	0.10 - 0.15	0.81 - 1.12	0.00846 - 0.00893	0.00000 - 0.00008
		Paintal - Uni of Minnesota: 2	9	0.0221	0.9	0.14 - 0.17	0.98 - 1.14	0.00860 - 0.00919	0.00013 - 0.00120
		Paintal - Uni of Minnesota: 3	9	0.0240	0.9	0.14 - 0.18	0.85 - 1.05	0.00790 - 0.00879	0.00022 - 0.00229
		Paintal - Uni of Minnesota: 4	34	0.0080	0.9	0.03 - 0.08	0.39 - 0.70	0.00207 - 0.00550	0.00000 - 0.00153
		Paintal - Uni of Minnesota: 5	30	0.0025	0.9	0.04 - 0.10	0.39 - 0.56	0.00117 - 0.00171	0.00000 - 0.00567
		Wilcock - MIT, Cambridge: 1 (MUNI)	6	0.0019	0.6	0.11 - 0.12	0.45 - 0.59	0.00096 - 0.00185	0.00000 - 0.01364
		Wilcock - MIT, Cambridge: 2 (CUNI)	4	0.0053	0.6	0.11	0.59 - 0.70	0.00255 - 0.00360	0.00000 - 0.00039
		Wilcock - MIT, Cambridge: 3 (0.5phi)	7	0.0018	0.6	0.11 - 0.11	0.44 - 0.58	0.00100 - 0.00220	0.00001 - 0.02052
		Wilcock - MIT, Cambridge: 4 (1.0phi)	6	0.0018	0.6	0.11	0.43 - 0.56	0.00104 - 0.00204	0.00002 - 0.01708
		Williams - USGS, Washington DC	29	0.0014	0.6 - 0.7	0.03 - 0.14	0.37 - 0.67	0.00060 - 0.00414	0.00140 - 0.07753
King *et al.*, 2004	Field	Big Wood River near Ketchum, Idaho	100	0.1190	12.8	0.41 - 0.73	1.15 - 1.68	0.00910	0.00004 - 0.02148
		Blackmare Creek, Idaho	88	0.1030	4.9 - 7.8	0.12 - 0.29	0.44 - 0.85	0.02990	0.00001 - 0.00104
		Boise River, Idaho	82	0.0760	52.4 - 55	0.57 - 1.04	1.11 - 1.71	0.00380	0.00033 - 0.03600
		Cat Spur Creek, Idaho	34	0.0270	3.8 - 5	0.19 - 0.30	0.23 - 0.51	0.01110	0.00000 - 0.00083
		Dollar Creek, Idaho	85	0.0870	7 - 9.7	0.16 - 0.25	0.33 - 0.80	0.01460	0.00000 - 0.00102
		Eggers Creek, Idaho	137	0.0228	0.7	0.08 - 0.21	0.21 - 0.47	0.07180	0.00006 - 0.00361
		Fourth of July Creek, Idaho	79	0.0510	6 - 6.8	0.12 - 0.28	0.21 - 0.64	0.02020	0.00000 - 0.00153
		Hawley Creek, Idaho	85	0.0400	4.2 - 5.6	0.13 - 0.18	0.46 - 0.71	0.02330	0.00002 - 0.00098
		Herd Creek, Idaho	70	0.0670	7.6 - 8.2	0.1 - 0.27	0.37 - 0.89	0.00770	0.00000 - 0.00923
		Johns Creek, Idaho	9	0.2070	10.6 - 14.1	0.38 - 0.68	0.48 - 1.17	0.02070	0.00000 - 0.00100
		Johnson Creek, Idaho	72	0.1900	18.3 - 22.1	0.48 - 0.93	0.71 - 1.44	0.00400	0.00001 - 0.00144
		Little Buckhorn Creek, Idaho	78	0.0810	1.4 - 2.9	0.12 - 0.25	0.21 - 0.41	0.05090	0.00000 - 0.00127
		Little Slate Creek, Idaho	157	0.1020	6.7 - 11.4	0.24 - 0.49	0.24 - 0.87	0.02680	0.00000 - 0.00069
		Lochsa River, Idaho	72	0.1260	67.1 - 73.1	0.85 - 1.27	1.92 - 2.40	0.00230	0.00001 - 0.00226
		Lolo Creek, Idaho	112	0.0680	8.5 - 11.4	0.21 - 0.63	0.43 - 0.74	0.00970	0.00001 - 0.00126
		Main Fork Red River, Idaho	200	0.0500	6.7 - 9.6	0.18 - 0.47	0.20 - 0.79	0.00590	0.00000 - 0.00299

Data Source	Data Type	Dataset	N	Surface material D_{50} (m)	Width (m)	Depth (m)	Average Velocity (m^1s^{-1})	Slope (m / m)	Transport rate per unit width ($kg^1m^{-1}s^{-1}$)
		Marsh Creek, Idaho	98	0.0560	8.8 - 16.5	0.27 - 0.50	0.38 - 1.04	0.00600	0.00000 - 0.00416
		Middle Fork Salmon River, Idaho	64	0.1460	42.7 - 62.4	1.17 - 1.61	1.67 - 2.72	0.00410	0.00007 - 0.10736
		North Fork Clearwater River, Idaho	70	0.0950	70.1 - 75.6	1.73 - 2.18	0.83 - 1.29	0.00050	0.00002 - 0.01478
		Rapid River, Idaho	190	0.0630	11.4 - 14.8	0.23 - 0.52	0.33 - 0.97	0.01080	0.00000 - 0.00561
		Salmon River below Yankee Fork, Idaho	60	0.1040	30.5 - 33.8	1.20 - 1.54	1.04 - 1.44	0.00340	0.00004 - 0.00788
		Salmon River nr Obsidian, Idaho	50	0.0610	12 - 13.3	0.66 - 0.83	0.91 - 1.30	0.00660	0.00065 - 0.02079
		Salmon River nr Shoup, Idaho	61	0.0960	46.5 - 84.5	1.08 - 2.11	1.91 - 2.39	0.00190	0.00094 - 0.10012
		Selway River, Idaho	72	0.1730	82.3 - 88	1.36 - 1.88	1.16 - 1.92	0.00210	0.00001 - 0.00336
		South Fork Payette River, Idaho	72	0.1100	43.6 - 48.3	0.44 - 0.85	0.91 - 1.48	0.00400	0.00097 - 0.03017
		South Fork Red River, Idaho	202	0.1060	5.8 - 8	0.13 - 0.40	0.19 - 0.73	0.01460	0.00000 - 0.00170
		South Fork Salmon River, Idaho	130	0.0380	29.6 - 32.4	0.54 - 1.40	0.24 - 0.90	0.00250	0.00001 - 0.02960
		Squaw Creek nr Clayton, Idaho	92	0.0460	3.3 - 9	0.24 - 0.37	0.14 - 0.71	0.01000	0.00000 - 0.00351
		Squaw Creek nr Papoose Creek, Idaho	42	0.0270	2.1 - 2.5	0.19 - 0.22	0.45 - 0.78	0.02400	0.00004 - 0.00233
		Thompson Creek, Idaho	84	0.0625	4.2 - 5.6	0.16 - 0.27	0.34 - 0.84	0.01530	0.00000 - 0.00399
		Trapper Creek, Idaho	166	0.0850	3.4 - 5	0.09 - 0.24	0.13 - 0.52	0.04140	0.00000 - 0.00177
		Valley Creek, Idaho	180	0.0400	18.4 - 27.6	0.38 - 0.51	0.49 - 0.85	0.00400	0.00000 - 0.00507
		West Fork Buckhorn Creek, Idaho	85	0.1800	5.9 - 8.8	0.17 - 0.30	0.24 - 0.70	0.03200	0.00001 - 0.00126
		Cache Creek nr Jackson, Wyoming	60	0.0460	5.1 - 5.2	0.29 - 0.38	0.50 - 0.75	0.02033 - 0.02094	0.00003 - 0.00068
		Coon Creek	88	0.0820	4.5 - 5.6	0.15 - 0.29	0.48 - 1.13	0.03100	0.00000 - 0.00452
		East Fork Encampment River	84	0.0480	3.9 - 5.5	0.10 - 0.23	0.29 - 0.79	0.03800	0.00000 - 0.00127
		East Fork San Juan	40	0.0500	15 - 16.4	0.27 - 0.43	0.71 - 1.32	0.00440 - 0.00755	0.00005 - 0.06274
Ryan *et al.*, 2005	Field	East St. Louis Creek	108	0.0510	2.8 - 2.9	0.17 - 0.28	0.35 - 0.83	0.05170 - 0.05680	0.00000 - 0.00348
		Fool Creek	95	0.0380	1.7 - 1.9	0.07 - 0.14	0.15 - 0.81	0.05200 - 0.05346	0.00000 - 0.00336
		Halfmoon Creek	155	0.0610	8.3 - 8.5	0.16 - 0.39	0.35 - 1.04	0.00917 - 0.01334	0.00001 - 0.01201
		Hayden Creek	78	0.0680	5.2 - 5.4	0.10 - 0.23	0.31 - 0.87	0.01518 - 0.02565	0.00001 - 0.00199
		Little Granite Creek	123	0.0890	9.6	-*	-*	0.02000	0.00000 - 0.01306
		Middle Fork Piedra River	85	0.0780	11.4 - 13.1	0.19 - 0.42	0.44 - 1.17	0.00900 - 0.01589	0.00000 - 0.01053

Data Source	Data Type	Dataset	N	Surface material D_{50} (m)	Width (m)	Depth (m)	Average Velocity ($m^1 s^{-1}$)	Slope (m / m)	Transport rate per unit width ($kg^1 m^{-1} s^{-1}$)
		Silver Creek	57	0.0280	3.8 - 4.1	0.11 - 0.28	0.46 - 0.82	0.03800 - 0.04475	0.00002 - 0.02161
		South Fork Cache Le Poudre	89	0.0680	7.3 - 12.6	0.16 - 0.41	0.34 - 1.09	0.00700	0.00000 - 0.00960
		St. Louis Creek 1	92	0.1280	6.4 - 6.7	0.16 - 0.36	0.38 - 1.05	0.01300 - 0.02066	0.00003 - 0.00937
		St. Louis Creek 2	104	0.0760	6.5 - 7.2	0.14 - 0.33	0.55 - 1.14	0.01100	0.00000 - 0.00791
		St. Louis Creek 3	98	0.0820	6.1 - 8.3	0.13 - 0.29	0.5 - 1.08	0.01100 - 0.01721	0.00001 - 0.00688
		St. Louis Creek 4	196	0.0910	6.2 - 6.9	0.19 - 0.35	0.62 - 1.25	0.01900	0.00000 - 0.00551
		St. Louis Creek 4a	173	0.0790	6.2 - 8.1	0.20 - 0.33	0.65 - 1.19	0.01900	0.00003 - 0.00693
		St. Louis Creek 5	84	0.1460	5.2 - 5.3	0.18 - 0.31	0.59 - 1.10	0.03500 - 0.05025	0.00003 - 0.00252
		Upper Florida River nr Lemon Reservoir	25	0.1810	11.3 - 14.5	0.41 - 0.64	0.27 - 0.95	0.00120 - 0.00814	0.00000 - 0.00058
Wilcock *et al.*, 2001	Flume	Wilcock – BOMC	10	0.0053	0.6	0.09 - 0.11	0.26 - 0.56	0.00060 - 0.00410	0.00000 - 0.08675
		Wilcock - J06	10	0.0122	0.6	0.10 - 0.11	0.74 - 0.97	0.00440 - 0.01073	0.00000 - 0.02501
		Wilcock - J14	9	0.0098	0.6	0.10 - 0.11	0.77 - 0.96	0.00440 - 0.01121	0.00002 - 0.02859
		Wilcock - J21	8	0.0084	0.6	0.10 - 0.11	0.66 - 0.86	0.00320 - 0.00873	0.00002 - 0.03981
		Wilcock - J27	10	0.0067	0.6	0.09 - 0.10	0.45 - 0.86	0.00100 - 0.00743	0.00000 - 0.13602
Yang, 1979	Field	Colby - Niobara River data	25	0.0003	21 - 21.4	0.41 - 0.47	0.62 - 0.88	0.00114 - 0.00141	0.11006 - 0.58744
		Einstein - Mountain Creek	61	0.0010	3.4 - 4.4	0.06 - 0.14	0.37 - 0.52	0.00136 - 0.00155	0.00121 - 0.01797
		Hubbell - Middle Loup River, Nebraska	15	0.0003	37.5 - 43.9	0.25 - 0.32	0.59 - 0.81	0.00093 - 0.00127	0.12671 - 0.35318
		Jordan - Mississippi River, near St. Louis	25	0.0002 - 0.0004	459.6 - 490.1	4.82 - 8.44	0.62 - 1.11	0.00004 - 0.00007	0.01247 - 0.73103
		Nordin - Rio Grande, near Bernalillo A2	21	0.0002 - 0.0003	40.5 - 80.2	0.71 - 1.01	0.83 - 1.56	0.00074 - 0.00081	0.22121 - 2.41933
		Nordin - Rio Grande, near Bernalillo F	21	0.0002 - 0.0003	102.1 - 158.6	0.33 - 0.60	0.62 - 1.33	0.00074 - 0.00081	0.05832 - 0.86697
	Flume	Gilbert - 0.305mm sand in 1.32ft flume	21	0.0003	0.4	0.02 - 0.03	0.44 - 0.68	0.00270 - 0.00884	0.02213 - 0.18190
		Gilbert - 0.305mm sand in 1.96ft flume	33	0.0003	0.6	0.02 - 0.04	0.31 - 0.77	0.00180 - 0.00831	0.01388 - 0.25137
		Gilbert - 0.375mm sand in 0.66ft flume	50	0.0004	0.2	0.01 - 0.05	0.48 - 0.84	0.00210 - 0.01209	0.02094 - 0.32985
		Gilbert - 0.375mm sand in 1.00ft flume	42	0.0004	0.3	0.02 - 0.06	0.32 - 0.75	0.00150 - 0.00847	0.00414 - 0.24944
		Gilbert - 0.375mm sand in 1.32ft flume	51	0.0004	0.4	0.01 - 0.04	0.33 - 0.82	0.00250 - 0.00985	0.01291 - 0.20990
		Gilbert - 0.375mm sand in 1.96ft flume	44	0.0004	0.6	0.01 - 0.05	0.35 - 0.77	0.00180 - 0.00834	0.01072 - 0.20220

Data Source	Data Type	Dataset	N	Surface material D_{50} (m)	Width (m)	Depth (m)	Average Velocity (m^1s^{-1})	Slope (m / m)	Transport rate per unit width ($kg^1m^{-1}s^{-1}$)
		Gilbert - 0.506mm sand in 0.44ft flume	15	0.0005	0.1	0.03 - 0.05	0.40 - 0.62	0.00610 - 0.01231	0.02383 - 0.22057
		Gilbert - 0.506mm sand in 0.66ft flume	63	0.0005	0.2	0.02 - 0.06	0.35 - 0.86	0.00200 - 0.00980	0.01146 - 0.33644
		Gilbert - 0.506mm sand in 1.00ft flume	61	0.0005	0.3	0.02 - 0.06	0.34 - 0.86	0.00130 - 0.00869	0.00524 - 0.33701
		Gilbert - 0.506mm sand in 1.32ft flume	46	0.0005	0.4	0.01 - 0.04	0.41 - 0.79	0.00160 - 0.01009	0.00337 - 0.23335
		Gilbert - 0.506mm sand in 1.96ft flume	49	0.0005	0.6	0.02 - 0.04	0.44 - 0.83	0.00350 - 0.00966	0.01595 - 0.24246
		Gilbert - 0.786mm sand in 0.66ft flume	36	0.0008	0.2	0.02 - 0.05	0.51 - 0.84	0.00190 - 0.01360	0.02637 - 0.38838
		Gilbert - 0.786mm sand in 1.00ft flume	53	0.0008	0.3	0.02 - 0.05	0.38 - 0.85	0.00180 - 0.01187	0.00656 - 0.38971
		Gilbert - 0.786mm sand in 1.32ft flume	26	0.0008	0.4	0.03 - 0.05	0.47 - 0.81	0.00300 - 0.00942	0.02739 - 0.24225
		Gilbert - 1.71mm sand in 0.66ft flume	12	0.0017	0.2	0.03 - 0.07	0.67 - 0.81	0.00560 - 0.01207	0.10456 - 0.18153
		Gilbert - 1.71mm sand in 1.00ft flume	28	0.0017	0.3	0.02 - 0.08	0.46 - 0.73	0.00180 - 0.00901	0.00558 - 0.15051
		Guy - CSU, 2ft wide flume, 0.32mm D50	31	0.0003	0.6	0.16 - 0.19	0.26 - 0.95	0.00014 - 0.00387	0.00000 - 1.97441
		Guy - CSU, 2ft wide flume, 0.33mm - G	17	0.0003	0.6	0.15 - 0.15	0.32 - 0.88	0.00022 - 0.00296	0.00000 - 1.12677
		Guy - CSU, 2ft wide flume, 0.33mm - U	14	0.0003	0.6	0.15 - 0.15	0.31 - 0.94	0.00025 - 0.00390	0.00000 - 1.03965
		Guy - CSU, 2ft wide flume, 0.54mm D50	38	0.0005	0.6	0.18 - 0.22	0.27 - 1.15	0.00016 - 0.00558	0.00000 - 2.11018
		Guy - CSU, 8ft wide flume, 0.19mm D50	40	0.0002	2.4	0.09 - 0.21	0.23 - 0.69	0.00006 - 0.00177	0.00000 - 1.27113
		Guy - CSU, 8ft wide flume, 0.27mm D50	20	0.0003	2.4	0.14 - 0.24	0.24 - 0.79	0.00007 - 0.00262	0.00000 - 1.38211
		Guy - CSU, 8ft wide flume, 0.28mm D50	37	0.0003	2.4	0.09 - 0.22	0.25 - 0.79	0.00007 - 0.00241	0.00000 - 1.05217
		Guy - CSU, 8ft wide flume, 0.45mm D50	45	0.0005	2.4	0.06 - 0.16	0.20 - 0.75	0.00015 - 0.00299	0.00000 - 0.41452
		Guy - CSU, 8ft wide flume, 0.47mm D50	54	0.0005	2.4	0.09 - 0.20	0.34 - 0.86	0.00042 - 0.00354	0.00013 - 0.57182
		Guy - CSU, 8ft wide flume, 0.93mm D50	43	0.0009	2.4	0.12 - 0.22	0.30 - 0.77	0.00013 - 0.00349	0.00000 - 0.36798
		Kennedy - 0.233mm sand in 0.875ft flume	14	0.0002	0.3	0.04 - 0.06	0.48 - 0.78	0.00260 - 0.00597	0.01672 - 0.40029
		Kennedy - 0.233mm sand in 2.79ft flume	13	0.0002	0.9	0.04 - 0.07	0.41 - 0.79	0.00170 - 0.00592	0.01116 - 0.61354
		Kennedy - 0.549mm sand in 0.875ft flume	14	0.0005	0.3	0.02 - 0.05	0.50 - 0.94	0.00550 - 0.01366	0.03811 - 0.49206
		Nomicos - 0.241 ft deep, 0.152mm	12	0.0002	0.3	0.07	0.24 - 0.43	0.00200 - 0.00242	0.00537 - 0.09330
		Nordin - 1976 Bernado sand	31	0.0001 - 0.0002	2.4	0.31 - 0.55	0.51 - 1.02	0.00014 - 0.00103	0.00748 - 0.98387
		Stein - 0.4mm sand in 4 ft flume	42	0.0004	1.2	0.18 - 0.25	0.42 – 10.00	0.00061 - 0.00349	0.01191 - 1.15176
		Vanoni - 0.137mm sand in 2.79ft flume	14	0.0001	0.9	0.06 - 0.11	0.23 - 0.45	0.00070 - 0.00187	0.00063 - 0.06152
		Williams - 1.35mm sand in 1ft flume	37	0.0014	0.3	0.03 - 0.09	0.39 - 0.60	0.00110 - 0.00531	0.00060 - 0.06689

6.3.2 Flow parameters associated with bed-load transport rate

Du Boys (1879) initially had the idea of using the tractive force of flowing water in the analysis of coarse material transport. Since his early study, numerous equations relating coarse material load to flow conditions and bed material composition have been proposed. Many of these equations are very similar and are commonly based around one of a few parameters that describe the flow responsible for transport. Some of these commonly applied flow parameters are described within this section (tractive force, mean velocity, specific (unit width) stream power and unit (unit weight) stream power), along with an explanation of how they have been related to bed-load transport. In addition, the derivation of a new parameter (unit width kinetic power) is described.

As mentioned above, much of the early development in the analysis of bed-load transport was influenced by the work of du Boys (1879). He based his predictions of bed-load transport rate on an approximation of the shear stress exerted by the velocity of the flow at the bed of a channel (u_b) using tractive force (τ) in $kg^1m^{-1}s^{-2}$

$$\tau = \rho_w \cdot g \cdot R \cdot S_e$$

Equation 6.1

where 'ρ_w' is the density of water (kg^1m^{-3}), 'g' is the acceleration due to gravity (m^1s^{-2}), 'R' is the hydraulic radius of the flow (m), and 'S_e' is the energy gradient of the flow (m^1m^{-1}). du Boys (1879) related tractive force to bed-load transport rate using

$$q_s = K \cdot \tau \cdot (\tau - \tau_c)$$

Equation 6.2

where q_s is the unit width bed-load transport rate ($kg^1m^{-1}s^{-1}$), K is related to sediment type, and τ_c is the critical tractive force necessary to entrain sediment particles ($kg^1m^{-1}s^{-2}$).

Numerous subsequent formulae designed to predict bed-load transport rate have been developed using the tractive force to approximate the hydrodynamic forces of drag and lift actually acting on grains at the bed. The most notable efforts include those by Shields (1936), Kalinske (1947), and more recently, by Wilcock and Crowe (2003).

Whilst tractive force is commonly used to approximate the forces exerted by flow on bed grains, the fundamental flaw within this approximation is not commonly understood. Little (1940) demonstrated that the assumption that the shear stress actually acting on the bed is directly proportional to the hydrostatic pressure of the flow is flawed because head loss and internal friction related to turbulence are independent of pressure. Hence, increasing depth at constant velocity does not change the kinetic energy of the flow per unit volume, but by increasing the distance between free surface and the bed, actually reduces turbulent intensity.

Like his peers who applied tractive force as an approximation of the near-bed flow velocities, Hjulström (1935) had identified that the velocity near the bed had the strongest influence on coarse material transport. However, rather than tractive force, Hjulström (1935) used mean velocity ($\bar{u}$) as a more practical alternative to near-bed velocity in the prediction of bed-load entrainment and transport. Hjulström's paper is widely referenced in relation to the prediction of the critical velocity for entrainment of sediment particles. However, despite this, relatively little known research has focused on the development of relationships between mean flow velocity and bed-load transport rate. The main reason for this is considered to be the difficulty in relating bottom velocity (u_b) to mean velocity.

As was briefly introduced in Section 2.5.3, the earliest known formalisation of a relation between the rate of energy expenditure, the debris-carrying capacity of the stream and the channel morphology, is credited by Clifford (2008) to the work of the American engineer, Seddon (1896). In the first of two investigations of river hydraulics, Seddon argued that energy expenditure depended on the 'size' of the river, measured by discharge, Q, and the fall in elevation, h. Later work by Gilbert (1914) was concerned with calculating whether bed-load added to (by increased mass) or subtracted from (by increasing viscosity and by transport) the total stream energy of channel flow, and with how total capacity could be limited by the transport of various size fractions. However, his attempts to quantify energy extraction by comparing the velocities of loaded and unloaded streams were inconclusive, partly because only bed texture and traction were considered as elements of flow resistance (Clifford, 2008).

In related work, Cook (1935) hypothesised that the total energy expenditure by flow in natural channels could be broken-down into multiple components, each of which was associated with hydraulic, fluid dynamic or transport phenomena such as viscous shear, turbulence, suspended sediment transport, bed-load transport, work on the channel boundaries, surface waves, and bed ripples. Cook's (1935) work laid the foundations for the rational approach to sediment transport that was substantially advanced by Bagnold (1966; 1973; 1977; 1979; 1980; 1983; 1986).

Bagnold (1966) is commonly credited with originating the concept of streams being sediment transport machines which can be analysed in terms of the availability of stream power to do work. Prior to Bagnold's work, hydraulic engineers had developed many different empirical formulae for sediment transport, each an approximation over a different limited range of conditions. Attempts to merge these formulae into a general empirical relationship, applicable under all conditions, had failed. Bagnold (1966) attempted to approach the sediment transport problem from the opposite direction using the principles of physics. He defined the total power available to a unit length of stream as *"the time rate of liberation in kinetic form of the liquid's potential energy as it descends the gravity slope"* (1966: 238). Rhoads (1987b) describes in detail the physical basis for Bagnold's stream power equation but in short, as a body of water moves through a given distance along an inclined channel, work is performed as the gravitational potential energy of the flowing water is converted to kinetic energy:

$$W = F \cdot \Delta x = \rho_w \cdot g \cdot A \cdot X \cdot S_e \cdot \Delta x$$

Equation 6.3

where 'W' is work done ($kg^1m^2s^{-2}$), 'F' is the shear force applied to the channel bed ($kg^1m^1s^{-2}$), 'Δx' is the distance moved by the flow downstream (m), 'A' is the cross-sectional area of flow (m^2), and 'X' is the length of the reach (m). The stream power of the water flowing through the reach is the time rate of energy loss, which is therefore:

$$P = \rho_w \cdot g \cdot A \cdot X \cdot S_e \cdot \bar{u} \cdot \Delta x = \rho_w \cdot g \cdot Q \cdot S_e \cdot \Delta x$$

Equation 6.4

where 'P' is the total stream power over the reach ($kg^1m^2s^{-3}$), '$\bar{u}$' is the mean velocity (m^1s^{-1}) and 'Q' is discharge (m^3s^{-1}). Stream power is now more commonly expressed in relation to unit length of stream:

$$\Omega = \rho_w \cdot g \cdot Q \cdot S_e \cdot \Delta x / X = \rho_w \cdot g \cdot Q \cdot S_e$$

Equation 6.5

where 'Ω' is the power per unit length of stream ($kg^1m^1s^{-3}$), or, as in the case of the majority of Bagnold's work, stream power is expressed in relation to unit channel width:

$$\omega = \frac{\Omega}{w} = \frac{\rho_w \cdot g \cdot Q \cdot S_e}{w} = \tau \cdot \bar{u}$$

Equation 6.6

where 'ω' is stream power per unit bed area, or stream power per unit bed area (kg^1s^{-3}), and 'w' is channel bed width (m).

In his published papers, Bagnold put forward several functions for coarse material transport based on stream power per unit bed area, including:

$$q_s = \frac{e \cdot \omega}{\tan \alpha}$$

Equation 6.7

where e is a factor representing the efficiency with which the available power is utilised for sediment transport, and α is the coefficient of dynamic solid friction.

Bagnold's approach has been widely praised for its conceptual attractiveness insofar as it treats rivers as work-performing machines with explicit attention to their efficiency (Ferguson, 2005). The stream power approach is also pragmatically convenient for the purposes of this study in that it can be approximated from gross channel properties that are obtainable from datasets widely available for British rivers (discharge, channel width and channel slope). These reasons, along with its performance in comparative tests (Gomez and Church, 1989; Martin and Church, 2000) explain why the stream power approach is used widely in broad-scale studies of fluvial geomorphology (Graf, 1983; Lawler, 1992b; Magilligan, 1992; Knighton, 1999).

Yang (1972) also attempted to relate the power of flowing water to sediment transport capacity. He stated that the only source of energy for a unit weight of water is its potential energy above a datum, and that the stream power of a unit weight of water is defined as the time rate of potential energy expenditure per unit weight of water. He derived his formula for unit weight stream power (VS) based on the representation of the time rate of potential energy expenditure as:

$$\frac{\Delta h}{\Delta t} = \frac{\Delta x}{\Delta t} \cdot \frac{\Delta h}{\Delta x} = VS$$

Equation 6.8

where 'h' is the elevation above a datum (m), which also equals the potential energy per unit weight of water, 't' is time (s) and 'x' is horizontal distance (m), enabling stream power per unit weight of water to be represented as a product of velocity and slope (assuming slope angle to be small so that $\cos\theta \approx \tan\theta$).

Like Bagnold's stream power per unit bed area, Yang's unit weight stream power approach to predicting sediment transport rate has been successfully applied empirically under a range of test conditions (Yang, 1996). Yang's (1972) formulation for the prediction of sediment transport is given by

$$\log C_t = A + B \cdot \log(VS - VS_c)$$

Equation 6.9

where C_t is total sediment concentration, A and B are coefficients and VS_c is the critical unit weight stream power required to initiate the motion of sediment particles.

The similar theoretical justifications for Yang's and Bagnold's stream power approaches suggests that they should be similar in terms of their representation of the potential for flow to perform geomorphic work. However, there is an apparent incongruity between these two representations of the power available to a stream. This incongruity can be recognised on the basis that Bagnold's approach of stream power per unit bed area is independent of variations in flow depth and velocity whilst Yang's approach of stream power per unit weight of water is not. This apparent lack of equivalence is explained by an important difference between Bagnold's stream power concept and Yang's unit stream power in that Bagnold's stream power gives rate of energy loss from water occurring over a *unit bed area* whilst Yang's parameter gives the rate of energy loss within a *unit weight of water* flowing over a bed. This point is clarified by the following example.

Consider the two flow conditions in Figure 6.1 with identical discharge, width, and slope but with differing depth/velocity relationships due to different levels of channel roughness. Under condition A (Manning's *n*=0.1), where velocity is twice that of B (Manning's *n*=0.04), the stream power per unit bed area as defined by Bagnold is identical to that under condition B. However, using Yang's definition of stream power per unit weight of water the value is twice as high under condition A as it is under condition B. The difference occurs because, under condition A, due to the velocity being twice as fast, the amount of bed over which each unit weight of water flows in a given time is twice that under condition B. This means that, whilst the energy loss per unit weight of water in 1 second may be twice as high under condition A, the energy loss from the unit weight of water under condition A is distributed over twice the downstream distance. This makes the stream power per unit weight of water delivered to a unit bed area equal under both flow conditions. This theoretical analysis demonstrates that whilst Yang's unit stream power appears to vary with depth, it does not predict any change in the power applied to the channel boundaries, which is what is important in understanding and predicting coarse sediment dynamics.

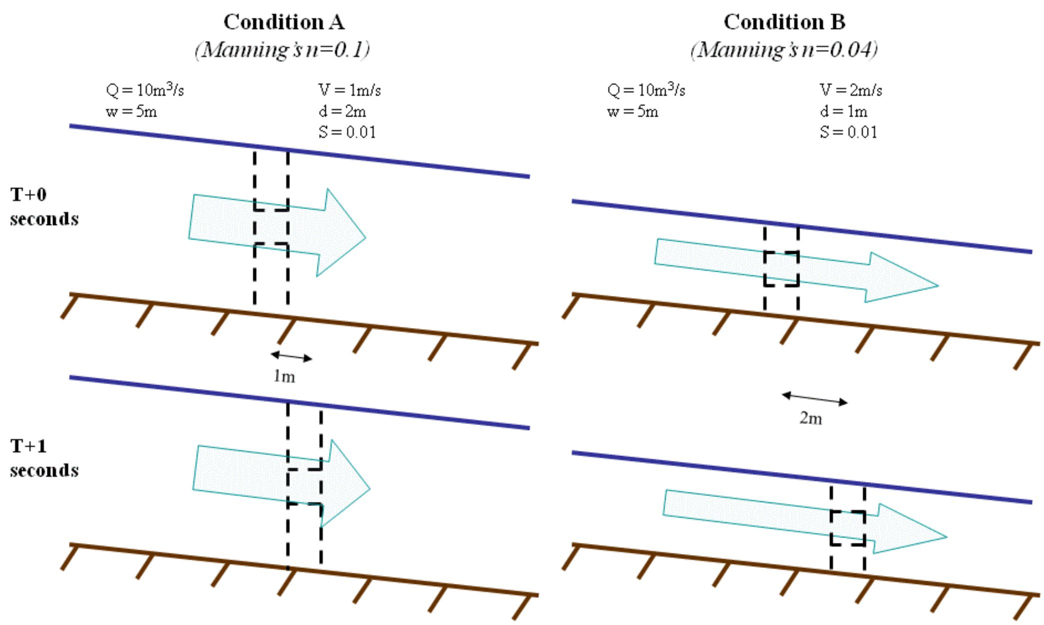


Figure 6.1 Representation of the differences between Bagnold's stream power per unit bed area and Yang's unit weight stream power for 2 conditions of similar slope and discharge but different channel roughness.

An alternative approach to representing the potential for a stream to perform geomorphic work has been derived from physical considerations, but in order to give it justification it is first necessary to clarify the definition of Bagnold's concept of stream power. Bagnold referred to his stream power parameter by various definitions across his papers: as the *"available power supply, or time rate of energy"* (1966: 238); as the *"time rate of liberation in kinetic form of the liquid's potential energy as it descends the gravity slope"* (1966: 238); as the *"rate of kinetic energy supply and dissipation"* (1980: 324); as the "*total dynamic power of a stream*" (1986: 346); as *"the total activating fluid power available"* (1986: 349) and also as the *"loss of gravity potential energy"* (1986: 349). Others have since used different definitions ranging from *"the amount of work that a river may do"* (Petit *et al.*, 2005: 93) to *"the time rate of conversion of potential energy to kinetic energy that is dissipated in overcoming internal and boundary friction, in transporting sediment and in eroding the channel perimeter"* (Ferguson, 2005: 191). Despite the confusing range of language used in these definitions, it is apparent that an important distinction can be made between the potential and kinetic energy possessed by a given body of fluid flowing down a slope, and the energy losses through turbulence and friction (and therefore heat) from that fluid. Indeed, Bagnold (1966) identified that the energy dissipated as heat is as little related to the energy contained within the fluid as the inflow and outflow of water through a reservoir is related to the quantity of water stored within it. It is on the rate of energy loss to heat, rather than on the energy possessed by a mass of fluid that Bagnold and all subsequent stream power researchers have concentrated their efforts. Whilst a proportion of this energy loss is caused by the transport of sediment through a system, a significant quantity is also lost to boundary friction and internal shearing within the water column. The difficulty with identifying the proportion of energy lost specifically to the transport of sediment (on which Bagnold's concept of efficiency was based) has led to consideration of an alternative framework for considering energy dynamics in rivers, based on quantifying the energy possessed by the fluid rather than attempting to separate the causes of energy losses.

Water with a mass 'm' entering a river at a height 'h' above a given datum has an amount of potential energy defined by:

$$E_p = m \cdot g \cdot h$$

Equation 6.10

where 'E_p' is the potential energy contained within the water. As this mass of water moves downslope, that potential energy is converted into kinetic energy:

$$E_k = \frac{1}{2} \cdot m \cdot \bar{u}^2$$

Equation 6.11

where 'E_k' is the kinetic energy contained within the flowing water.

In a conservative system, the law of energy conservation means that the sum of the kinetic and potential energy should remain constant and any loss in potential energy should be matched by an equivalent gain in kinetic energy. However, rivers are non-conservative systems and friction through boundary and internal shear cause a significant proportion of the available mechanical energy to be dissipated in the form of heat, which cannot perform mechanical work (Simons and Senturk, 1992). The rate of this total energy loss is what is represented by both Bagnold's and Yang's concepts of stream power. The energy balances within flowing water can be demonstrated through examination of the Bernoulli energy equation, a widely accepted concept in elementary hydraulics, which considers the total energy per unit weight of water, or head (H), in any channel section (Chow, 1973). For channels of small slope this is equal to the sum of the elevation of the channel above a datum (z), the pressure head or depth of flow (d) and the velocity head of the flow in the stream line ($\frac{\bar{u}^2}{2 \cdot g}$) (Figure 6.2).

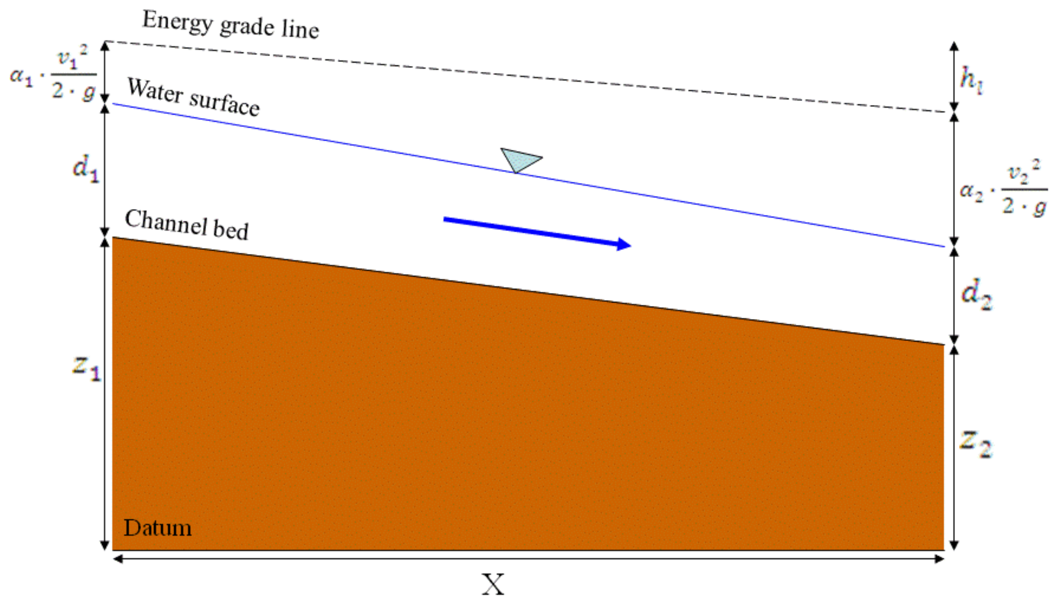


Figure 6.2 Graphical representation of the energy equation for steady gradually varied flow.

$$H = z + d + \alpha \cdot \frac{\bar{u}^2}{2 \cdot g}$$

Equation 6.12

where 'α' is the energy coefficient used to correct for the overall effect of non-uniform velocity distributions (Chow, 1973). The line between two points representing the total head of flow at two sections is the energy grade line. As identified above, in conservative systems, there is no loss of energy – any loss in channel elevation should be balanced by an increase in flow depth and/or velocity head. This would imply an energy line with a slope (energy gradient) of zero. However, in reality because of energy losses within the flow and at the channel boundary the total head of flow at the downstream section will be lower than at the upstream section so that:

$$z_1 + d_1 + \alpha_1 \cdot \frac{\bar{u}_1^{\,2}}{2 \cdot g} = z_2 + d_2 + \alpha_2 \cdot \frac{\bar{u}_2^{\,2}}{2 \cdot g} + h_l$$

Equation 6.13

where 'h_l' is the head (energy per unit weight of water) loss between the two sections. With respect to the stream power concepts addressed earlier, the time rate at which this head loss occurs is equivalent to Yang's (1972) unit weight stream power, justifying Yang's definition as the time rate of potential energy expenditure per unit weight of water. Whilst this h_l represents the energy per unit weight lost from the system, the sum of the elevation of the channel above a datum and the depth of flow ($z + d$) represents the potential energy above the arbitrary datum per unit weight since:

$$(z + d) \cdot m \cdot g = m \cdot g \cdot h$$

Equation 6.14

and importantly, the velocity head ($\frac{\bar{u}^2}{2 \cdot g}$) represents the kinetic energy per unit weight since:

$$\frac{v^2}{2 \cdot g} \cdot m \cdot g = \frac{1}{2} \cdot m \cdot v^2$$

Equation 6.15

Therefore, in a similar manner to which Bagnold's stream power represents the time rate of energy loss for a unit channel length by:

$$\Omega = \frac{h_l \cdot m \cdot g}{t \cdot X} = \frac{V \cdot S_e \cdot A \cdot X \cdot \rho_w \cdot g}{X} = \rho_w \cdot g \cdot Q \cdot S_e$$

Equation 6.16

the time rate of kinetic energy delivery to a unit channel length is:

$$\mathrm{P_k} = \frac{\frac{\bar{u}^2}{2 \cdot g} \cdot m \cdot g}{t \cdot X} = \frac{\frac{1}{2} \cdot m \cdot \bar{u}^2}{t \cdot X} = \frac{\rho_w \cdot Q \cdot \bar{u}^2}{2 \cdot X}$$

Equation 6.17

where 'P_k' represents the rate of kinetic energy delivery or *kinetic power* per unit channel length. It is proposed that, whilst the energy losses from fluid flow due to friction (stream power) may be related to sediment transport as the shearing involved in sediment transport is partly responsible for those energy losses, the actual kinetic energy of the fluid flow may also be related to sediment transport since it is this that is responsible for driving the motion of grains. Therefore, it is proposed that the sediment transport capacity should be causally related to the rate of kinetic energy delivery (kinetic power), represented by Equation 6.17.

This idea of fluid possessing kinetic power is well recognised in the application of fluid mechanics to hydropower calculations. The rate of hydrodynamic energy delivery to electricity generating devices is often expressed in relation to the rate at which a given mass of fluid is lowered by a height (h):

$$\mathrm{P_p} = \rho_w \cdot Q \cdot g \cdot h$$

Equation 6.18

where 'P_p' is the rate of conversion of available potential energy, or *Potential Power*. However, this power can also be expressed in terms of the rate of delivery of the kinetic energy of flowing water, or *Kinetic Power* where:

$$\mathrm{P_k} = \gamma \cdot Q \cdot \frac{\bar{u}^2}{2 \cdot g} = \frac{\rho_w \cdot A \cdot \bar{u}^3}{2} = \frac{\rho_w \cdot Q \cdot \bar{u}^2}{2}$$

Equation 6.19

$$\mathrm{K} = \frac{\rho_w \cdot Q \cdot \bar{u}^2}{2 \cdot w} = \frac{\rho_w \cdot \bar{d} \cdot \bar{u}^3}{2}$$

Equation 6.20

where K is the kinetic power of fluid per unit channel width.

There is an apparent parallel between the mechanical work that water performs in turning a waterwheel or turbine and the mechanical work performed by water in transporting sediment along a channel. Therefore, it is proposed that the kinetic power of flowing fluid per unit channel width could be used as a new parameter with which to predict the amount of geomorphological work performed on the channel boundaries.

6.3.3 Identification of the flow parameter most appropriate for predicting coarse material transport rate

To identify the most appropriate flow parameter for predicting transport rate in a general sediment transport formula, Spearman's Rank correlation coefficients were calculated between each of the parameters described above and transport rate for each of the datasets within the collated database. All of the hydraulic parameters apart from unit weight stream power have been correlated against unit width bed-load transport rate. Unit weight stream power has been correlated against sediment concentration as suggested by Yang (1972). Spearman's Rank has been selected as an appropriate statistical means to identify the parameter best associated with sediment transport rate as a strong positive correlation ($R = 1$) does not assume anything about the nature of the relationship between two variables, other than that an increase in one is associated with an increase in another (Davis, 2002). This means that no assumptions regarding the type of relationship (linear versus power versus exponential) between the flow parameters and transport rate are necessary.

It should be noted that a particularly important limitation with all of the parameters under consideration above is that they are hydraulic in nature and therefore only depth-averaged representations of the flow responsible for coarse material transport. It is recognised that unsteadiness and non-uniformity in the flow are important for coarse material transport; however, they are not considered here due to the difficulties in representing them at the broad-scale under consideration within this study.

6.3.4 Accounting for supply limitations within bed-load transport data

As has been highlighted previously within this thesis, transport capacity is the maximum sediment load that a given discharge can transport. This is only achieved when the supply of sediment to the channel equals or exceeds the transport capacity, and presents an important limitation in the utilisation of many bed-load transport datasets when deriving a bed-load transport capacity relationship which assumes no supply limitation. By definition, empirically derived sediment transport capacity relationships must be derived using datasets that are transport-, and not supply-, limited. Therefore, before using any of the collated datasets, it was considered appropriate to attempt to remove any datasets where sediment supply limitations restrict measured transport rates to less than the capacity value.

Bravo-Espinosa *et al.* (2003) described a semi-quantitative process for identifying whether bed-load transport data are representative of supply- or transport-limited conditions. They examined exponential relations between bed-load transport rate and stream power per unit bed area. Based on the assumption that any lack of relation between bed-load transport rate and stream power is due to the non-uniform spatio-temporal distribution of mobile sediment they identified whether a stream is transport-limited using the statistical significance of the relationship between its sediment discharge and stream power. This assumption seems reasonable because where no supply limitations are present there should be a functional relation between sediment discharge and stream power. Datasets which are potentially supply-limited were identified as those where the slope of the relationship between transport rate and stream power does not differ significantly from zero for all mobilised particle sizes. Datasets where the slope of the relationship between bed-load transport rate and stream power does not differ significantly from zero for some, but not all, mobilised particle sizes were identified as being partially supply-limited, whilst datasets where there was a significant relationship between transport rate and stream power for all particle sizes were designated as transport-limited (Bravo-Espinosa *et al.*, 2003).

The technique applied here differs to that used by Bravo-Espinosa *et al.* (2003), but the underlying principle is the same. Based on the assumption that a poor correlation between bed-load transport rate and stream power is due to limitations on the supply of mobile material, a dataset is designated as supply- or transport-limited based upon the strength of the Spearman's Rank correlation between its bed-load transport rate and the hydraulic parameter most strongly correlated with transport rate. Datasets in the collated database were defined as transport-limited only if the Spearman's Rank correlation coefficient between bed-load transport rate and the hydraulic parameter identified as being most suitable for predicting transport rate falls above a selected threshold value of 0.75.

6.3.5 Separating bed surface material transport rates from bed-load transport rates

Bed-load sediment transport in coarse-grained channels has been described as occurring in phases (Jackson and Beschta, 1982; Carling, 1989; Ryan *et al.*, 2002), whereby transport rates are relatively low (Phase I) until a certain flow level is reached. Transport rates increase substantially once this threshold is exceeded, typically accompanied by an increase in the size of material moved (Phase II). Phase I transport consists primarily of material finer than that which dominates the bed surface, with the finer particles moving over a stable bed surface composed of coarser particles. This phase represents either remobilisation of finer fractions deposited in pools and tranquil areas of the bed, or involves the throughput of finer fractions delivered from upstream. Phase II consists of transport of these finer fractions along with the coarse material representative of the bed surface and, in armoured streams, the finer bed material previously hidden beneath the surface. It is only during this second phase that the transport of coarse material representative of the bed surface begins.

The idea of two-phase bed-load transport highlights an important difference between the bed-load transport of grains representative of the local channel bed surface, and the bed-load transport of grains that are not dominant components of the bed surface but which are, instead, sourced from either upstream reaches, or local, but temporary, pockets of fine material. Clearly, it is difficult to make *a priori* predictions about the nature of this type of Phase I transport, both in terms of the calibre of sediment particles in transit and the rate, because the rate of supply is unknown and the sizes are not apparent from examination of the size distribution on the bed. Further, transport of grain sizes not commonly observed on the bed surface locally can dominate the overall transport rate (e.g. Figure 6.3A). Based on the above, it can be considered an unrealistic expectation for an empirically derived sediment transport equation to be developed that could correctly and consistently predict total bed-load transport rates within natural streams. There are two reasons for this: firstly, to develop such an equation would require an empirical sediment transport dataset that also includes information on the total mass and size of all sediment supplied to the measurement site; and secondly, to apply such an equation would require knowledge of not just the hydraulic conditions and bed surface material size on the bed but also the mass and size of all sediment supplied to the study site.

Therefore, in deriving a transport capacity relationship that is based upon empirical datasets that commonly lack information on the nature of sediment supplied to the measurement sites and that can be applied without information on the nature of sediment supplied to the study sites, it is necessary to isolate the transfer rate of the sediment fraction observed locally on the bed surface from the remainder of bed-load transport. Focussing on the sediment sizes representative of the local bed surface material means that the resultant *bed surface material* transport relationship can be linked to determining factors that are known *a priori* – such as the sediment size observed on the bed surface and the intensity of the flow. In essence, by dealing solely with sediment fractions representative of the bed surface it is possible to ensure that the resultant expression for sediment transport is not influenced by the supply-limitations that influence the finer fractions. This is not possible with many *bed-load* transport formulae, which do not differentiate between the transport of material on the river bed surface from that of supply-limited finer material provided from upstream and elsewhere.

To isolate the coarse bed surface material load from the finer bed-load fractions for each dataset, the bed surface and bed-load size distributions were compared (Figure 6.3). A number of attempts were made to define a methodology that could objectively identify which fractions within the transported bed-load were representative of the bed surface. However, due to an inherent difficulty in defining what 'permanent' bed surface material consists of no objective means could be identified. For example, in some cases using all fractions that were observed in the bed surface distribution provided an obvious distinction between those sediment fractions that could be considered representative of the bed surface, and those that could not: the field-based uni-modal bed surface material size distribution in Figure 6.3A and the flume-based uni-modal bed surface material size distribution in Figure 6.3B. However, in other cases, using all fractions that were observed in the bed surface distribution led to the inclusion of finer material at sites with a bi-modal bed surface distribution (e.g. Figure 6.3C). However, using all fractions that were observed in the dominant 'mode' of the bed surface distribution led to further difficulties determining where the dominant bed surface mode ended and the other began. As a result of these difficulties in deriving an objective and consistent means of isolating the fractions representative of the bed surface each of the datasets was addressed separately and the size threshold at which sediment was considered large enough to be representative of the bed material surface was chosen on a case by case basis using expert judgement. As exemplified by the datasets in Figure 6.3A and Figure 6.3B, this could often be done based on the smallest size observed on the bed surface. However, in cases such as Figure 6.3C a somewhat subjective decision making process was employed. Once the lower size threshold for sediment fractions considered to be bed surface material was identified for each dataset the transport rate of all fractions above this threshold could be found for each bed-load measurement within that dataset – this provided the bed surface material transport rate.

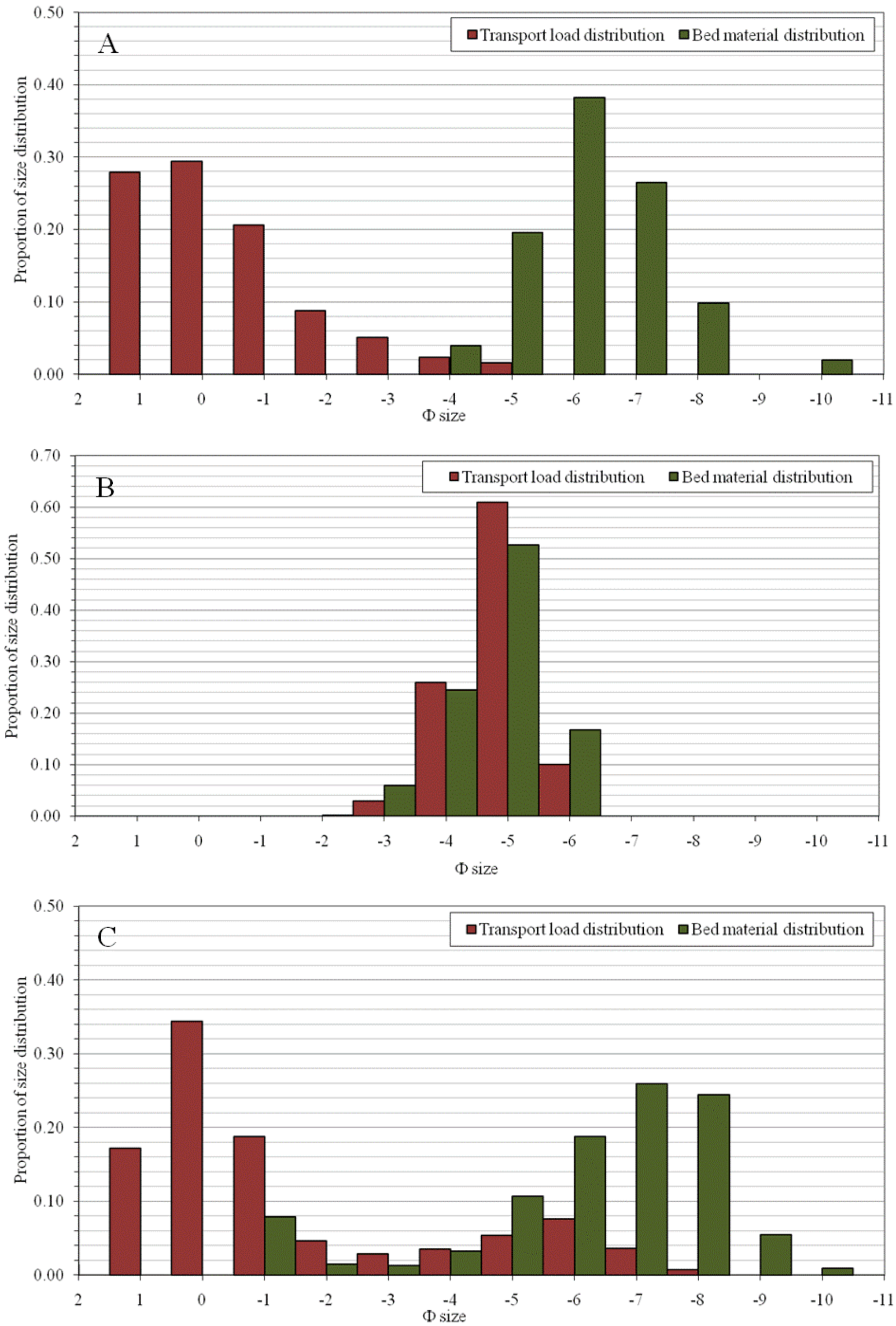


Figure 6.3 Examples of difference between bed surface material size distributions and transported size distributions. (A) Run taken from King et al.'s (2004) data for the Fourth of July Creek, Idaho. (B) Run taken from Wilcock et al.'s (2001) data for a flume-based experiment using sediment mixture 'J06'. (C) Run taken from King et al.'s (2004) data for the South Fork Payette River, Idaho.

6.3.6 Identification of a general bed surface material transport relationship using dimensionless parameters

To derive a general relationship between the selected hydraulic parameter, the observed bed surface material size, and the bed surface material transport rate, all of the datasets found to be transport-limited based on the distinction outlined in Section 6.3.4 were considered. For each of the observations, the rate of bed surface material transport was plotted against the parameter selected to represent flow intensity. However, the collated datasets include bed-load transport observations from a range of conditions, including both flume and field based measurements, and sediment calibres ranging from fine sand to large cobble. Therefore, it is expected that, when all of the datasets are plotted together in their conventional units, no observable trend will be present due to the overriding influence of the variations in conditions under which they were measured. To adjust for this, and enable a single, general trend to be found across all of the datasets, both the parameter chosen to represent flow intensity and the sediment transport rate must be made dimensionless. Making both the parameter chosen to represent flow intensity and the sediment transport rate dimensionless allows the properties of these physical quantities to be considered independently of the units used to measure them. This form of analysis should therefore enable a generally consistent relationship to be derived between the parameter chosen to represent flow intensity and the transport rate of local bed surface material.

6.4 Results and analysis

6.4.1 Identification of flow parameter most appropriate for predicting coarse material transport rate

The Spearman's Rank correlation coefficient for each of the five flow parameters under consideration and bed-load transport rate was found for all 133 of the collated datasets. The results of these correlations are detailed in Table 6.2 and the distributions of correlation coefficients are illustrated in Figure 6.4.

These results demonstrate that, across all of the collated datasets, stream power per unit bed area (ω) has a stronger mean correlation coefficient with sediment transport rate than any of the other flow parameters (0.85). Mean velocity also has a relatively high correlation coefficient (0.83), with tractive force (mean bed shear stress), unit weight stream power and unit width kinetic power averaging correlation coefficients of 0.77, 0.74 and 0.78 respectively.

Not only is the mean association between stream power per unit bed area and transport rate stronger than any of the other flow parameters, but the strength of association is consistently greater across the majority of the collated datasets. Figure 6.4 demonstrates that not only do far more datasets have a correlation coefficient greater than 0.9 between stream power per unit bed area and bed-load transport rate than for any other parameter, but also, no other parameter has fewer datasets with correlation coefficients less than 0.5.

Furthermore, detailed analysis of the correlations for both velocity and tractive force for individual datasets reveal that, in certain datasets, they are very poorly associated with bed-load transport rate, despite stream power having a strong relationship in the same datasets (e.g. Figure 6.5).

Table 6.2 Spearman's Rank correlation coefficients between each flow parameter and bed-load transport rate for all datasets. Datasets in italic have been identified as supply-limited (a - unit weight stream power correlated against sediment concentration instead of transport rate)

Data Source	Data Type	Dataset	V	τ	ω	VS[a]	K
Bravo-Espinosa, 1999	Field	Clearwater River at Spalding, Idaho	0.83	0.85	0.84	0.63	0.83
		Snake River near Anatone, Washington	*0.52*	*0.55*	*0.53*	*0.35*	*0.53*
		East Fork River, Wyoming	*0.69*	*0.70*	*0.70*	*0.46*	*0.70*
		Oak Creek near Corvallis, Oregon	0.93	0.96	0.94	0.90	0.93
		Chippewa River at Durand, Wisconsin	0.85	0.81	0.83	0.21	0.83
		Chippewa River at Pepin, Wisconsin	*0.49*	*0.34*	*0.44*	*0.20*	*0.53*
		Horse Creek near Westcreek, Colorado	*0.80*	*0.53*	*0.74*	*0.73*	*0.80*
		La Garita Creek, Colorado	0.82	0.57	0.75	0.42	0.80
		N Fork South Platte River at Buffalo, Col.	*0.69*	*0.41*	*0.63*	*0.65*	*0.67*
		N Fork Toutle River at Kid Valley, Wash.	0.82	0.65	0.78	0.60	0.85
		Toutle River at Tower Road, Wash.	0.81	0.75	0.78	0.44	0.81
		Williams Fork near Leal, Colorado	*0.57*	*0.48*	*0.51*	*-0.44*	*0.56*
		Wiscosin River at Muscoda, Wisc.	*0.65*	*0.35*	*0.40*	*-0.16*	*0.63*
		Yampa River at Deerlodge Park, Col.	*0.51*	*0.17*	*0.25*	*-0.40*	*0.30*
Gomez and Church, 1989	Field	*Tanana River, Alaska*	*0.32*	*0.59*	*0.52*	*0.12*	*0.35*
		Elbow River, Alberta	0.81	0.84	0.81	0.72	0.81
	Flume	Ikeda - Uni of Tsukuba	0.93	0.95	0.97	0.96	0.75
		Johnson - IHR, Uni of Iowa: 1	0.42	0.75	0.74	0.81	-0.23
		Johnson - IHR, Uni of Iowa: 2	0.63	0.77	0.89	0.83	0.18
		Johnson - IHR, Uni of Iowa: 3	0.65	0.85	0.92	0.79	0.30
		Johnson - IHR, Uni of Iowa: 4	0.84	0.93	0.97	0.76	0.60
		Johnson - IHR, Uni of Iowa: 5	0.77	0.85	0.95	0.82	0.24
		Johnson - IHR, Uni of Iowa: 6	0.80	0.88	0.97	0.79	0.42
		Meyer-Peter & Muller - 1	0.79	0.89	0.89	0.94	0.45
		Meyer-Peter & Muller - 2	0.97	0.98	0.98	0.84	0.98
		Meyer-Peter & Muller - 3	0.96	0.89	0.96	0.96	0.96
		Paintal - Uni of Minnesota: 1	0.90	0.90	0.90	0.84	0.90
		Paintal - Uni of Minnesota: 2	0.81	0.78	0.78	0.73	0.82
		Paintal - Uni of Minnesota: 3	0.79	0.93	0.80	0.70	0.80
		Paintal - Uni of Minnesota: 4	0.80	0.93	0.93	0.65	0.82
		Paintal - Uni of Minnesota: 5	0.92	0.98	0.98	0.85	0.97
		Wilcock - MIT, Cambridge: 1 (MUNI)	1.00	1.00	1.00	1.00	1.00
		Wilcock - MIT, Cambridge: 2 (CUNI)	1.00	1.00	1.00	1.00	1.00
		Wilcock - MIT, Cambridge: 3 (0.5phi)	1.00	1.00	1.00	1.00	1.00
		Wilcock - MIT, Cambridge: 4 (1.0phi)	1.00	1.00	1.00	1.00	1.00
		Williams - USGS, Washington DC	0.93	0.96	0.96	0.99	0.60
King *et al.*, 2004	Field	Big Wood River near Ketchum, Idaho	0.94	0.94	0.94	0.89	0.94
		Blackmare Creek, Idaho	*0.74*	*0.55*	*0.71*	*0.53*	*0.75*
		Boise River, Idaho	0.93	0.93	0.93	0.84	0.93
		Cat Spur Creek, Idaho	*0.70*	*0.71*	*0.70*	*0.57*	*0.70*
		Dollar Creek, Idaho	0.83	0.80	0.83	0.67	0.83

Data Source	Data Type	Dataset	V	τ	ω	VS[a]	K
		Eggers Creek, Idaho	0.82	0.81	0.81	0.47	0.81
		Fourth of July Creek, Idaho	0.86	0.86	0.86	0.75	0.86
		Hawley Creek, Idaho	*0.54*	*0.49*	*0.52*	*0.30*	*0.53*
		Herd Creek, Idaho	0.86	0.87	0.87	0.76	0.86
		Johns Creek, Idaho	0.80	0.80	0.80	0.69	0.80
		Johnson Creek, Idaho	0.95	0.92	0.93	0.89	0.94
		Little Buckhorn Creek, Idaho	*0.62*	*0.80*	*0.72*	*0.38*	*0.67*
		Little Slate Creek, Idaho	*0.67*	*0.65*	*0.67*	*0.37*	*0.67*
		Lochsa River, Idaho	0.85	0.86	0.86	0.81	0.86
		Lolo Creek, Idaho	*0.44*	*0.53*	*0.49*	*0.11*	*0.47*
		Main Fork Red River, Idaho	0.79	0.78	0.79	0.57	0.79
		Marsh Creek, Idaho	0.80	0.56	0.75	0.72	0.81
		Middle Fork Salmon River, Idaho	0.79	0.81	0.81	0.74	0.80
		North Fork Clearwater River, Idaho	0.89	0.83	0.88	0.84	0.89
		Rapid River, Idaho	*0.74*	*0.71*	*0.73*	*0.55*	*0.74*
		Salmon River below Yankee Fork, Idaho	0.82	0.82	0.81	0.71	0.81
		Salmon River nr Obsidian, Idaho	*0.71*	*0.61*	*0.70*	*0.59*	*0.70*
		Salmon River nr Shoup, Idaho	*0.30*	*0.73*	*0.57*	*0.21*	*0.42*
		Selway River, Idaho	0.95	0.94	0.95	0.92	0.95
		South Fork Payette River, Idaho	0.82	0.81	0.82	0.63	0.82
		South Fork Red River, Idaho	*0.64*	*0.60*	*0.63*	*0.36*	*0.64*
		South Fork Salmon River, Idaho	0.87	0.85	0.86	0.77	0.86
		Squaw Creek nr Clayton, Idaho	0.86	0.72	0.85	0.73	0.86
		Squaw Creek nr Papoose Creek, Idaho	*0.57*	*0.28*	*0.52*	*0.39*	*0.56*
		Thompson Creek, Idaho	0.90	0.87	0.89	0.87	0.90
		Trapper Creek, Idaho	*0.71*	*0.67*	*0.70*	*0.39*	*0.71*
		Valley Creek, Idaho	*0.73*	*-0.14*	*0.62*	*0.65*	*0.73*
		West Fork Buckhorn Creek, Idaho	*0.61*	*0.54*	*0.59*	*0.35*	*0.60*
		Cache Creek nr Jackson, Wyoming	0.87	0.85	0.87	0.76	0.87
		Coon Creek	0.83	0.86	0.87	0.72	0.86
		East Fork Encampment River	0.73	0.74	0.78	0.65	0.77
		East Fork San Juan	*0.92*	*0.64*	*0.72*	*0.68*	*0.94*
		East St. Louis Creek	0.72	0.61	0.77	0.60	0.76
		Fool Creek	0.67	0.74	0.80	0.56	0.76
		Halfmoon Creek	0.92	0.85	0.90	0.80	0.92
		Hayden Creek	0.88	0.82	0.89	0.73	0.88
Ryan *et al.*, 2005	Field	Middle Fork Piedra River	0.93	0.88	0.92	0.86	0.93
		Silver Creek	*0.71*	*0.14*	*0.65*	*0.64*	*0.81*
		South Fork Cache Le Poudre	0.94	0.92	0.94	0.85	0.94
		St. Louis Creek 1	0.86	0.81	0.86	0.64	0.87
		St. Louis Creek 2	0.88	0.87	0.90	0.74	0.89
		St. Louis Creek 3	0.89	0.89	0.91	0.83	0.90
		St. Louis Creek 4	*0.69*	*0.59*	*0.70*	*0.54*	*0.70*
		St. Louis Creek 4a	0.74	0.61	0.77	0.63	0.79
		St. Louis Creek 5	*0.61*	*0.57*	*0.65*	*0.36*	*0.64*
		Upper Florida River nr Lemon Reservoir	0.96	0.91	0.93	0.90	0.97
Wilcock	Flume	Wilcock - BOMC	1.00	0.99	1.00	1.00	1.00

Data Source	Data Type	Dataset	V	τ	ω	VS[a]	K
et al., 2001		Wilcock - J06	0.95	0.99	1.00	1.00	0.95
		Wilcock - J14	1.00	0.93	0.95	0.98	1.00
		Wilcock - J21	0.96	0.95	0.95	0.98	0.90
		Wilcock - J27	0.98	1.00	1.00	0.99	1.00
Yang, 1979	Field	Colby - Niobara River data	0.95	0.91	0.95	0.92	0.96
		Einstein - Mountain Creek	0.94	0.93	0.93	0.84	0.92
		Hubbell - Middle Loup River, Nebraska	*0.87*	*-0.69*	*0.43*	*0.44*	*0.84*
		Jordan - Mississippi River, near St. Louis	0.95	0.91	0.94	0.89	0.93
		Nordin - Rio Grande, near Bernalillo A2	0.89	0.67	0.89	0.79	0.91
		Nordin - Rio Grande, near Bernalillo F	0.83	0.72	0.84	0.71	0.83
	Flume	Gilbert - 0.305mm sand in 1.32ft flume	0.91	0.94	0.99	0.96	0.83
		Gilbert - 0.305mm sand in 1.96ft flume	0.83	0.95	0.96	0.98	0.65
		Gilbert - 0.375mm sand in 0.66ft flume	0.84	0.95	0.98	0.98	0.64
		Gilbert - 0.375mm sand in 1.00ft flume	0.90	0.94	0.98	0.99	0.68
		Gilbert - 0.375mm sand in 1.32ft flume	0.88	0.86	0.97	0.97	0.72
		Gilbert - 0.375mm sand in 1.96ft flume	0.80	0.80	0.97	0.96	0.80
		Gilbert - 0.506mm sand in 0.44ft flume	0.98	0.98	0.99	0.90	0.88
		Gilbert - 0.506mm sand in 0.66ft flume	0.94	0.94	0.98	0.92	0.79
		Gilbert - 0.506mm sand in 1.00ft flume	0.95	0.94	0.99	0.97	0.82
		Gilbert - 0.506mm sand in 1.32ft flume	0.94	0.89	0.98	0.98	0.73
		Gilbert - 0.506mm sand in 1.96ft flume	0.93	0.92	0.98	0.99	0.71
		Gilbert - 0.786mm sand in 0.66ft flume	0.95	0.94	0.97	0.95	0.70
		Gilbert - 0.786mm sand in 1.00ft flume	0.98	0.97	0.99	0.98	0.84
		Gilbert - 0.786mm sand in 1.32ft flume	0.93	0.87	0.95	0.98	0.58
		Gilbert - 1.71mm sand in 0.66ft flume	0.84	0.94	0.93	0.79	0.86
		Gilbert - 1.71mm sand in 1.00ft flume	0.92	0.94	0.97	0.98	0.63
		Guy - CSU, 2ft wide flume, 0.32mm D50	0.97	0.96	0.97	0.97	0.98
		Guy - CSU, 2ft wide flume, 0.33mm D50 - G	0.98	0.99	0.99	0.98	0.98
		Guy - CSU, 2ft wide flume, 0.33mm D50 - U	1.00	0.95	1.00	1.00	1.00
		Guy - CSU, 2ft wide flume, 0.54mm D50	0.97	0.92	0.98	0.98	0.97
		Guy - CSU, 8ft wide flume, 0.19mm D50	0.97	0.97	1.00	0.99	0.96
		Guy - CSU, 8ft wide flume, 0.27mm D50	0.98	0.95	0.99	0.98	0.97
		Guy - CSU, 8ft wide flume, 0.28mm D50	0.98	0.93	0.98	0.99	0.96
		Guy - CSU, 8ft wide flume, 0.45mm D50	0.97	0.97	0.99	0.98	0.96
		Guy - CSU, 8ft wide flume, 0.47mm D50	0.96	0.93	0.97	0.96	0.94
		Guy - CSU, 8ft wide flume, 0.93mm D50	0.99	0.98	0.99	0.98	0.95
		Kennedy - 0.233mm sand in 0.875ft flume	0.92	0.88	0.93	0.94	0.82
		Kennedy - 0.233mm sand in 2.79ft flume	0.94	0.93	0.97	0.95	0.85
		Kennedy - 0.549mm sand in 0.875ft flume	0.98	0.90	0.96	0.98	0.90
		Nomicos - 0.241 ft deep, 0.152mm	0.99	-0.20	0.80	0.94	0.99
		Nordin - 1976 Bernado sand	0.96	0.58	0.94	0.93	0.93
		Stein - 0.4mm sand in 4 ft flume	0.99	0.48	0.92	0.98	0.97
		Vanoni - 0.137mm sand in 2.79ft flume	0.90	0.05	0.82	0.88	0.82
		Williams - 1.35mm sand in 1ft flume	0.92	0.99	0.98	0.99	0.57
Mean			**0.83**	**0.77**	**0.85**	**0.74**	**0.78**

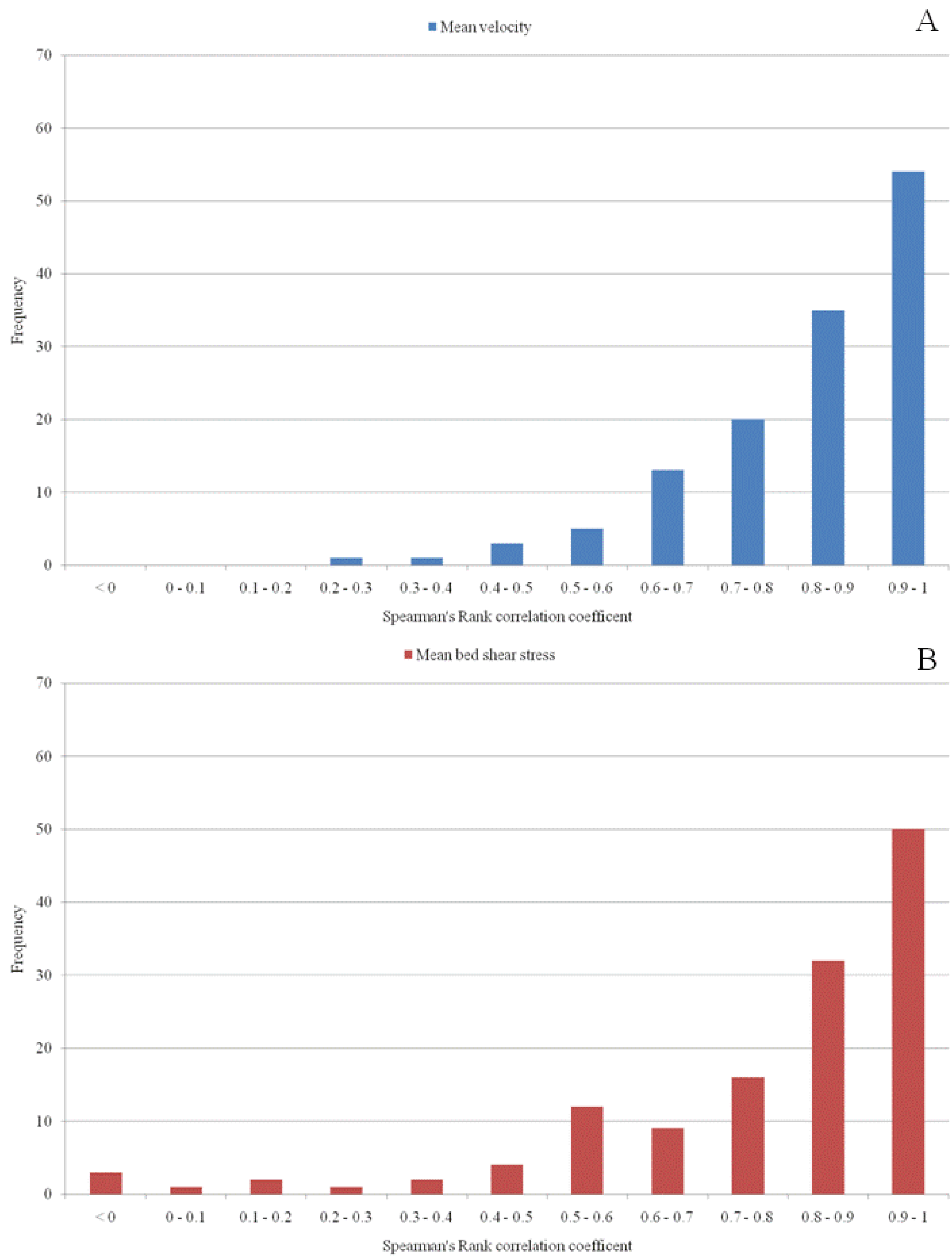


Figure 6.4 Distribution of Spearman's Rank correlation coefficients for flow parameters across transport datasets. (A) Mean velocity. (B) Tractive force.

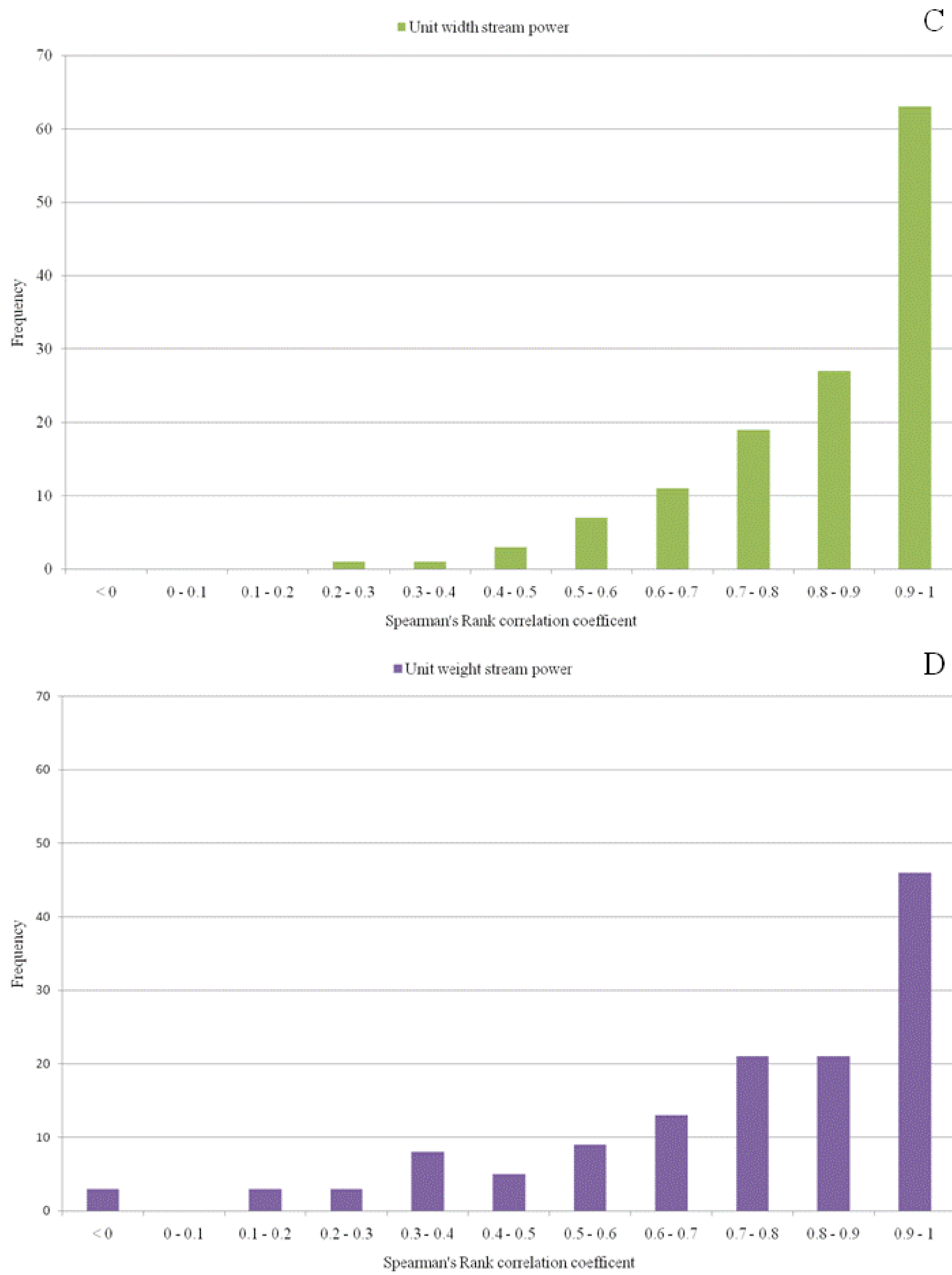


Figure 6.4 Distribution of Spearman's Rank correlation coefficients for flow parameters across transport datasets. (C) Stream power per unit bed area. (D) Unit weight stream power.

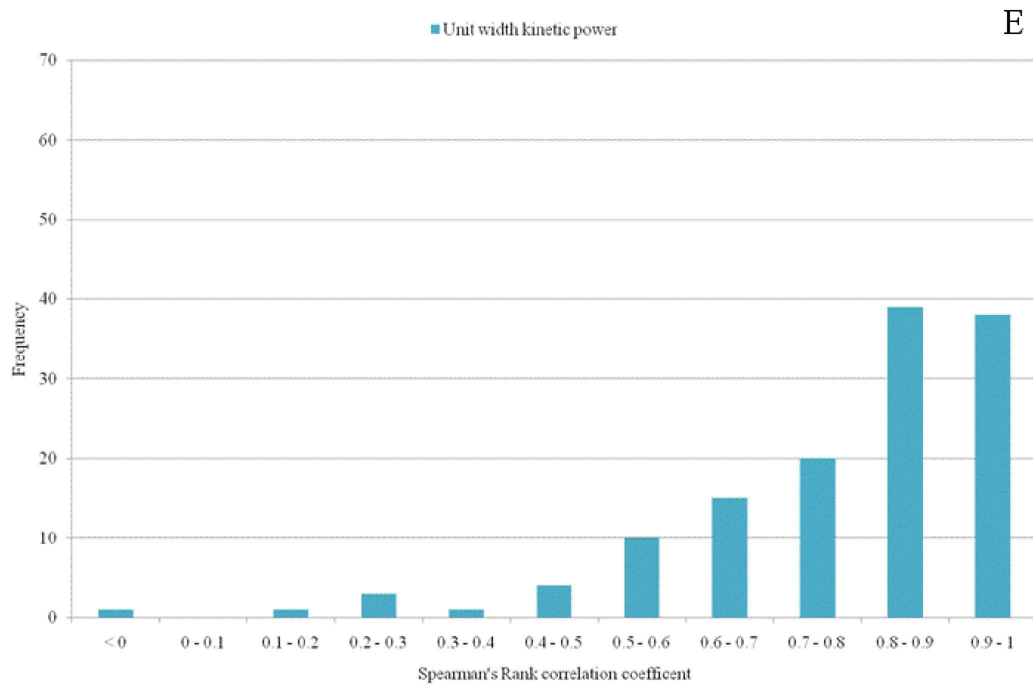


Figure 6.4 Distribution of Spearman's Rank correlation coefficients for flow parameters across transport datasets. (E) Unit width kinetic power.

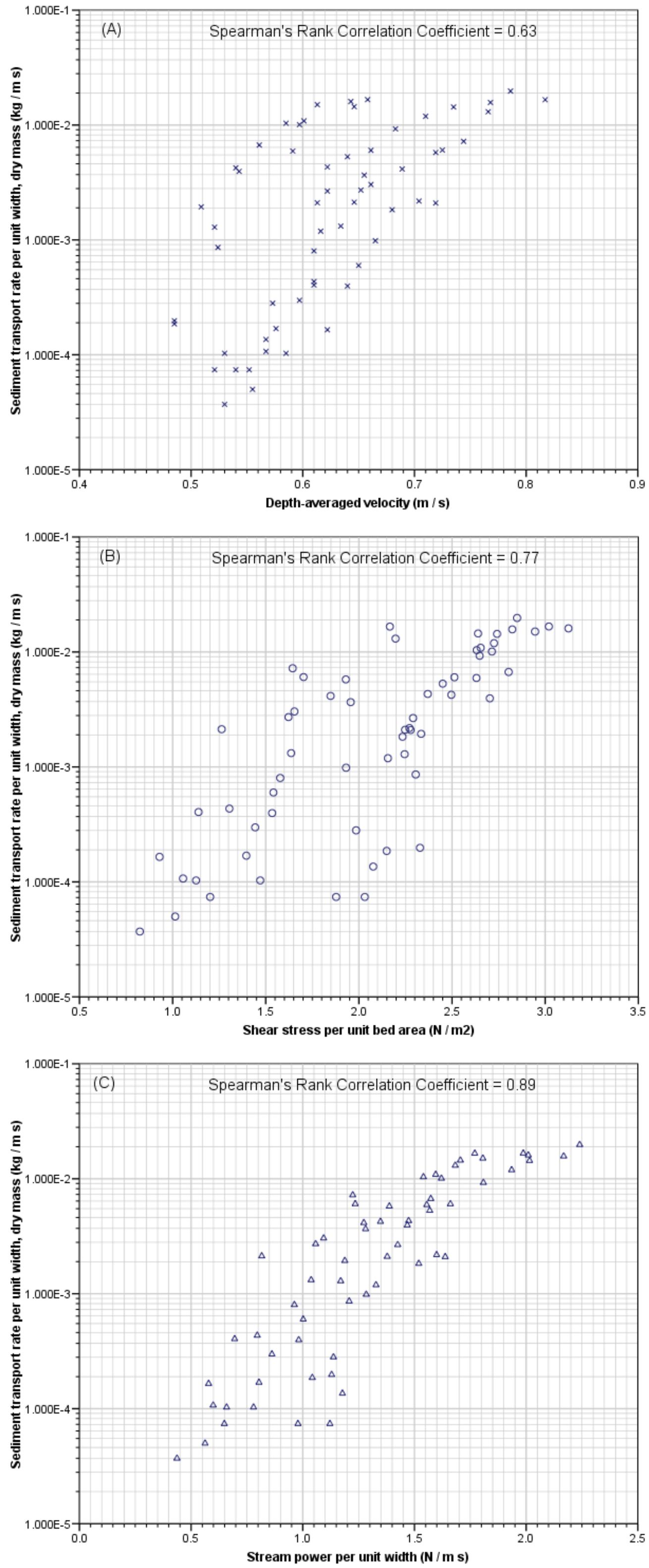


Figure 6.5 Examples of a sediment transport data set where (A) depth-averaged velocity and (B) tractive force are poorly correlated with sediment transport rate compared with (C) stream power per unit bed area - Johnson's (1943) laboratory investigations on bed-load transportation, series II, taken from the Gomez and Church (1988) collection of data.

6.4.2 Accounting for supply limitations within bed-load transport datasets

As described in Section 6.3.4, a filtering process was applied to all of the collated datasets to ensure that they are all transport-, rather than supply-, limited. Section 6.4.1 identified that stream power per unit bed area is the parameter most closely correlated with sediment transport rate. Therefore, datasets where the Spearman's Rank correlation coefficient fell below 0.75 were identified as not being transport-limited and are highlighted in italics in Table 6.2.

To evaluate this means of identifying non-transport-limited datasets Table 6.3 compares the classification of some datasets using this correlation threshold of 0.75 against the results of the classification applied by Bravo-Espinosa *et al.* (2003). This comparison illustrates how the two techniques produce a similar outcome – all of the datasets identified as transport and supply-limited by Bravo-Espinosa *et al.* (2003) are also identified as transport- and non-transport-limited respectively by the approach adopted here.

As a result of the above findings, it was concluded that the method applied here is sufficiently robust and only datasets with a Spearman's Rank correlation coefficient between sediment transport rate and stream power per unit bed area greater or equal to 0.75 were taken forward to be used within the derivation of a general formula for predicting bed surface material transport capacity.

Table 6.3 Identification of non-transport-limited datasets using Spearman's Rank coefficient compared with results of methodology applied by Bravo-Espinosa et al. (2003)

Dataset	**Bed-load transport condition identified by Bravo-Espinosa *et al.***	**Spearman's Rank correlation coefficient between stream power per unit bed area and unit width transport rate**	**Bed-load transport condition based on Spearman's Rank correlation coefficient**
Clearwater River at Spalding, Idaho	Partially supply limited	0.84	Transport limited
Snake River near Anatone, Washington	Supply limited	0.53	Not-transport limited
East Fork River, Wyoming	Partially supply limited	0.70	Not-transport limited
Oak Creek near Corvallis, Oregon	Transport limited	0.94	Transport limited
Chippewa River at Durand, Wisconsin	Transport limited	0.83	Transport limited
Chippewa River at Pepin, Wisconsin	Supply limited	0.44	Not-transport limited
Horse Creek near Westcreek, Colorado	Partially supply limited	0.74	Not-transport limited
La Garita Creek, Colorado	Transport limited	0.87	Transport limited
North Fork of South Platte River at Buffalo, Colorado	Partially supply limited	0.63	Not-transport limited
North Fork Toutle River at Kid Valley, Washington	Transport limited	0.78	Transport limited
Toutle River at Tower Road, Washington	Partially supply limited	0.78	Transport limited
Williams Fork near Leal, Colorado	Supply Limited	0.51	Not-transport limited
Wiscosin River at Muscoda, Wisconsin	Partially supply limited	0.40	Not-transport limited
Yampa River at Deerlodge Park, Colorado	Supply limited	0.25	Not-transport limited
Boise River, Idaho	Transport limited	0.93	Transport limited
Johnson Creek, Idaho	Transport limited	0.93	Transport limited
Lochsa River, Idaho	Transport limited	0.86	Transport limited
North Fork Clearwater River, Idaho	Transport limited	0.88	Transport limited
Selway River, Idaho	Transport limited	0.95	Transport limited
South Fork Payette River, Idaho	Transport limited	0.82	Transport limited
South Fork Salmon River, Idaho	Transport limited	0.86	Transport limited
Valley Creek, Idaho	Partially supply limited	0.62	Not-transport limited

6.4.3 Separating bed surface material transport rates from bed-load transport rates

Separation of the *bed surface material* transport rate from the total bed-load transport rate was performed for all the collated datasets. Figure 6.3 gives examples of how the transported material and local bed surface material size distributions differ for selected datasets. It is evident that, whilst the bed surface and bed-load size distributions from the flume-based example are similar, the bed surface and bed-load size distributions from the field-based example differ. As would be expected, the flume-based example shows that, where all of the material in the transport system is from the same mixture, the transported bed-load is generally similar in calibre to the material on the bed. In contrast, the field-based example demonstrates clearly that the majority of the transported bed-load may be finer than any of the material observed on the bed. Figure 6.6 demonstrates, for two of the datasets used in Figure 6.3, how the bed surface transport rate differs from the total bed-load transport rates. This is useful in demonstrating the impact of isolating the bed surface material transport rate. In this figure, a clear difference between the surface and total transport rates is apparent in the field-based example. This is because a large proportion of the bed-load is no longer included as it is finer than that present on the bed surface. This clearly has important implications for formulae that predict bed-load transport rates based on the sediment sizes observed on the bed, but which are derived or calibrated using total bed-load transport rates.

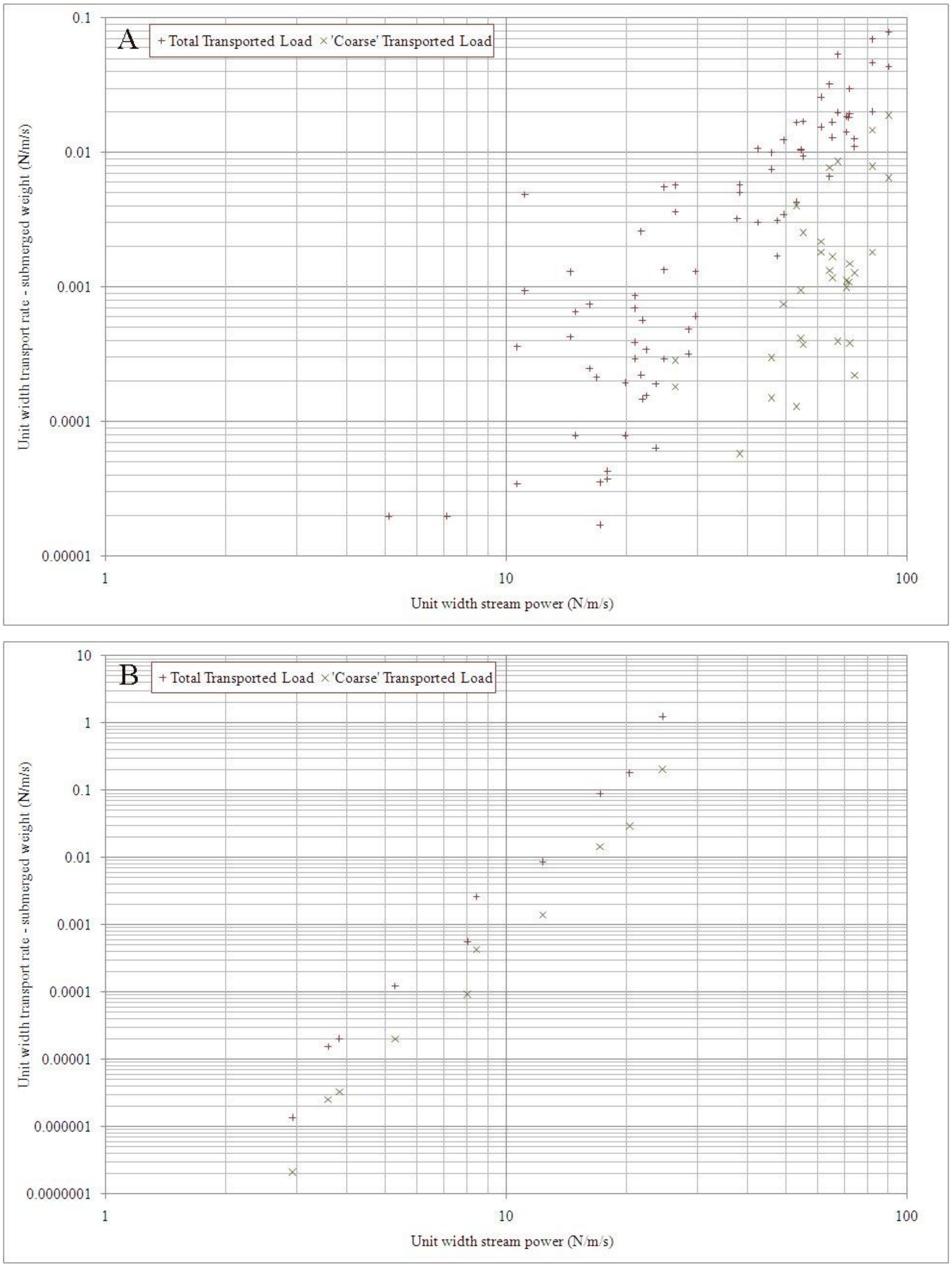


Figure 6.6 Examples of difference between total bed-load transport rates, and bed surface material transport rates. (A) King et al.'s (2004) data for the Fourth of July Creek, Idaho. (B) Wilcock et al.'s (2001) data for a flume-based experiment using sediment mixture 'J06'.

6.4.4 Identification of a general bed surface material transport function using dimensionless stream power per unit bed area

One criticism of the stream power per unit bed area approach as adopted by Bagnold is the lack of equality of units on either side of the equation. In their commonly used forms, the dimensions of stream power per unit bed area (W^1m^{-2} or $N^1m^{-1}s^{-1}$ - $M^1L^0T^{-3}$) and unit width sediment transport rate ($kg^1m^{-1}s^{-1}$ - $M^1L^{-1}T^{-1}$) are dissimilar. To solve this, Bagnold generally omitted the constant for gravitational acceleration from his representations of stream power per unit bed area, so that stream power per unit bed area and unit width sediment transport had the same units ($kg^1m^{-1}s^{-1}$ - $M^1L^{-1}T^{-1}$). However, this alternative expression for stream power has caused much confusion (Ferguson, 2005). As a solution, it is proposed here that sediment transport rate is described in terms of its submerged weight (Newtons) rather than mass (kg) so that both stream power per unit bed area and unit width sediment transport rate can be reported in $N^1m^{-1}s^{-1}$ ($M^1L^0T^{-3}$). Figure 6.7 displays all of the transport-limited datasets in these units.

Despite clear trends being present in Figure 6.7 for each of the transported sediment size types, there are significant differences between the relationships for each sediment size. This was expected based on the discussion in Section 6.3.6, and as a solution the stream power per unit bed area and unit width sediment transport rate values have been converted into non-dimensional forms. Since both stream power per unit bed area and unit width sediment transport rate (submerged weight) have the same units ($N^1m^{-1}s^{-1}$) they can be made dimensionless using the same denominator. The method for converting them into non-dimensionless form has been adapted from Einstein and Chien's (1955) dimensionless form of sediment transport rate used in attaining similarity in distorted river models. The non-dimensional version of stream power per unit bed area (ω^*) is therefore given by:

$$\omega^* = \frac{\omega}{g \cdot (\rho_s - \rho_w) \cdot \sqrt{\frac{\rho_s - \rho_w}{\rho_w} \cdot g \cdot {D_i}^3}}$$

Equation 6.21

and the non-dimensional version of unit width sediment transport rate (q_s^*) is given by:

$$q_s^* = \frac{q_s}{g \cdot (\rho_s - \rho_w) \cdot \sqrt{\frac{\rho_s - \rho_w}{\rho_w} \cdot g \cdot D_i{}^3}}$$

Equation 6.22

where q_s is the predicted rate of bed surface material transport in $N^1m^{-1}s^{-1}$ (submerged weight), w is the active channel width in m, ω is the stream power per unit bed area in $N^1m^{-1}s^{-1}$ calculated using $\omega = (Q \cdot S \cdot g \cdot \rho_w)/w$, Q is the discharge in m^3s^{-1}, S is the energy slope (approximated by channel slope), g is gravitational acceleration in m^2s^{-1} (assumed to be 9.81), ρ_s is the density of sediment in kg^1m^{-3} (assumed to be 2650), ρ_w is the density of water in kg^1m^{-3} (assumed to be 1000), and D_i is the assumed diameter of the bed surface material being transported in m^1.

These two dimensionless parameters have been plotted against each other in Figure 6.8 where a two-phase relationship is clearly apparent. Best-fit lines have been derived for each of the phases of the relationship and these are also displayed in Figure 6.8. The resultant functions fitted to the observations is

$$q_s^* = \begin{cases} 100 \cdot \omega^{*6} & \text{for } \omega^* < 0.25 \\ 0.2 \cdot \omega^{*1.5} & \text{for } \omega^* \geq 0.25 \end{cases}$$

Equation 6.23

As both parameters have been rendered dimensionless by dividing by the same denominator it is prudent to ensure that this relationship is not entirely spurious. A spurious relationship is one in which two occurrences have no causal connection, yet it may seem as though they do because of a common third factor (Benson, 1965), which in this case would be the common denominator used to make them dimensionless. When the same denominator was applied to a randomised dataset the relationship between the dimensionless random stream power and transport rate values was as illustrated by Figure 6.9. This shows that, whilst the common denominator between the dimensionless variables results in a spurious correlation, that correlation is far weaker than that for the real sediment transport data. Spearman's Rank correlation coefficients of 0.611 and 0.926 were obtained for the random and real datasets, respectively. Further, the relationship between the dimensionless random stream power and sediment transport values in Figure 6.9 does not exhibit the two-stage relationship apparent in Figure 6.8.

Figure 6.10 shows observed bed surface material transport values for some example datasets that fall within the first phase of the relationship ($\omega^* < 0.25$) alongside the relationship predicted by Equation 6.23. There is a varying degree of scatter around the relationship in this phase, but examination of the residuals demonstrates little discernable trend (Figure 6.11). Residuals were calculated as the ratio of predicted to observed values of q_s^* and have been plotted against both ω^* (Figure 6.11A), and bed surface material size type (Figure 6.11B).

Figure 6.12 shows observed bed surface material transport values for some example datasets that fall within the second phase of the relationship ($\omega^* \geq 0.25$) alongside the relationship predicted by Equation 6.23. Again, there is a varying degree of scatter around the best fit relationship for this phase. Inspection of the residuals for this phase (Figure 6.13) suggests that there is some over-prediction of bed surface material transport rates at the lower values of ω^* for some observations (Figure 6.13A). Observations that fall below the rate predicted by the relationship can also be seen in Figure 6.8 for values of dimensionless stream power per unit bed area of between ~0.25 and ~10. Closer examination of these observations reveals that they are all from a collection of datasets from one experimental programme: that of Guy *et al.* (1966), taken from Yang's collection of data (1979). It is hypothesised here that supply limitations were operating within this experimental set-up. Other than observations from this one particular source, there is no discernable trend in the residuals with either ω^* (Figure 6.13A), or bed surface material size type (Figure 6.13B).

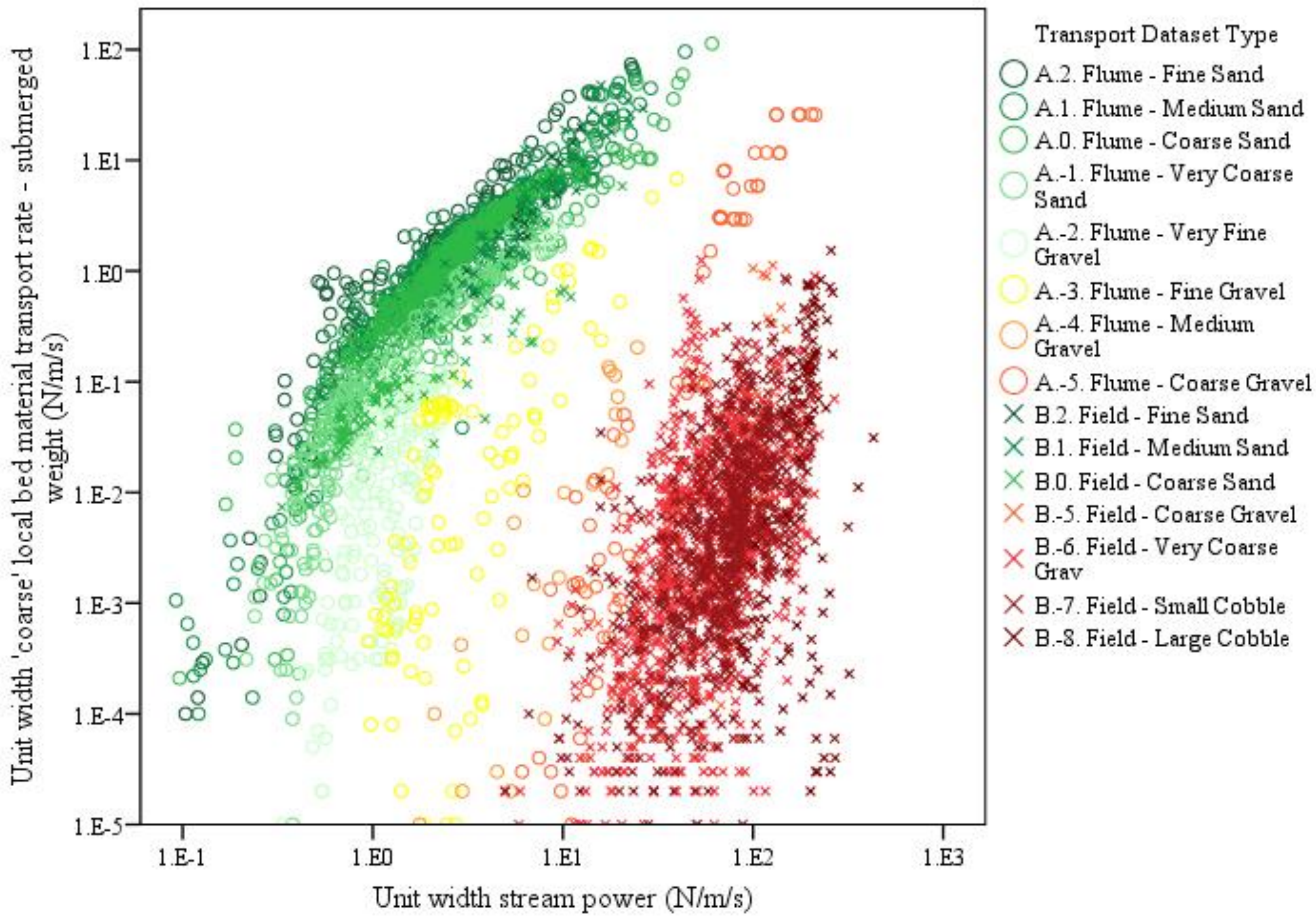


Figure 6.7 Unit width bed surface material transport rates plotted against stream power per unit bed area for all of the collated transport-limited datasets.

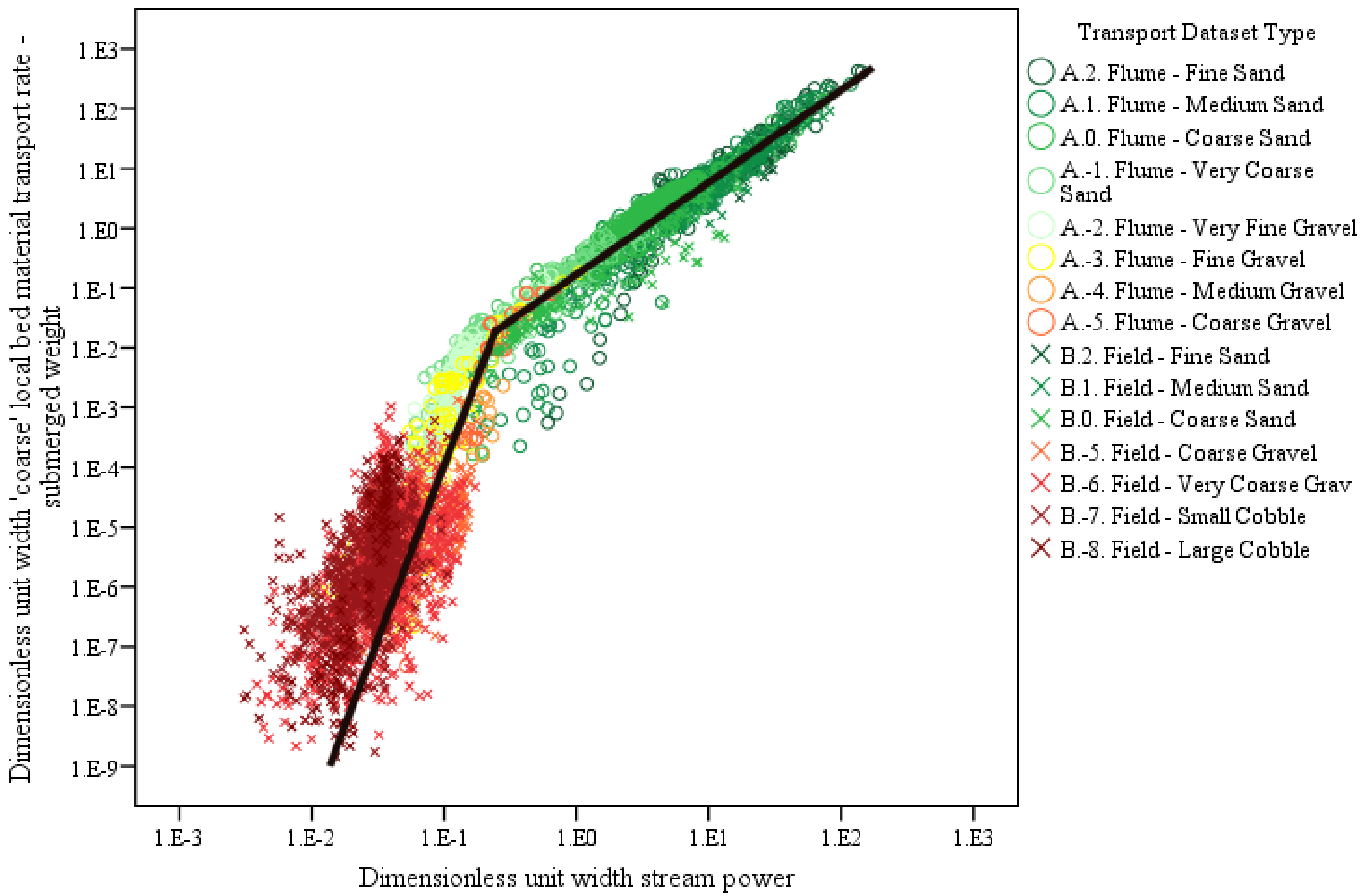


Figure 6.8 Dimensionless unit width bed surface material sediment transport rates plotted against dimensionless stream power per unit bed area for all of the collated transport-limited datasets. Solid line indicates derived two-phase bed surface material transport relationship.

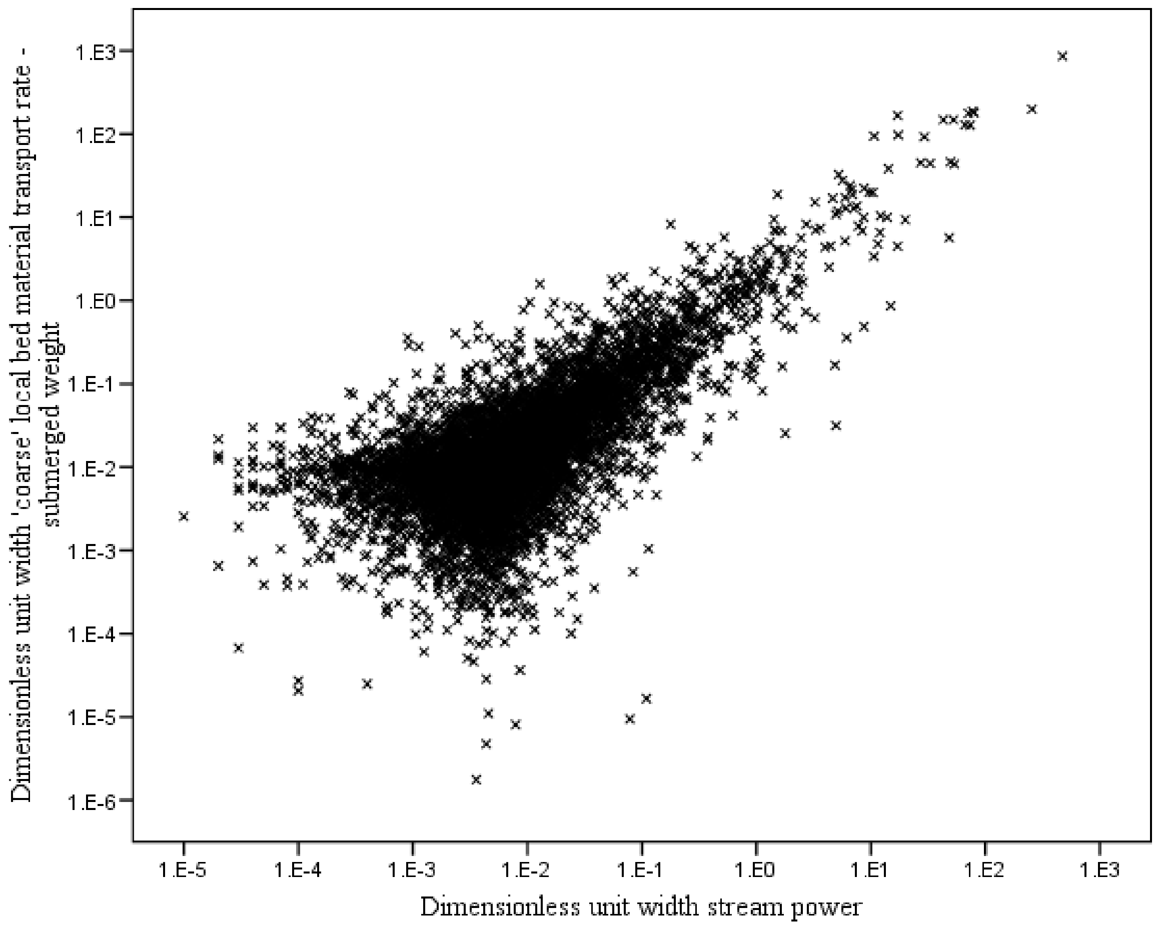


Figure 6.9 Dimensionless unit width bed surface material sediment transport rates plotted against dimensionless stream power per unit bed area for a random dataset

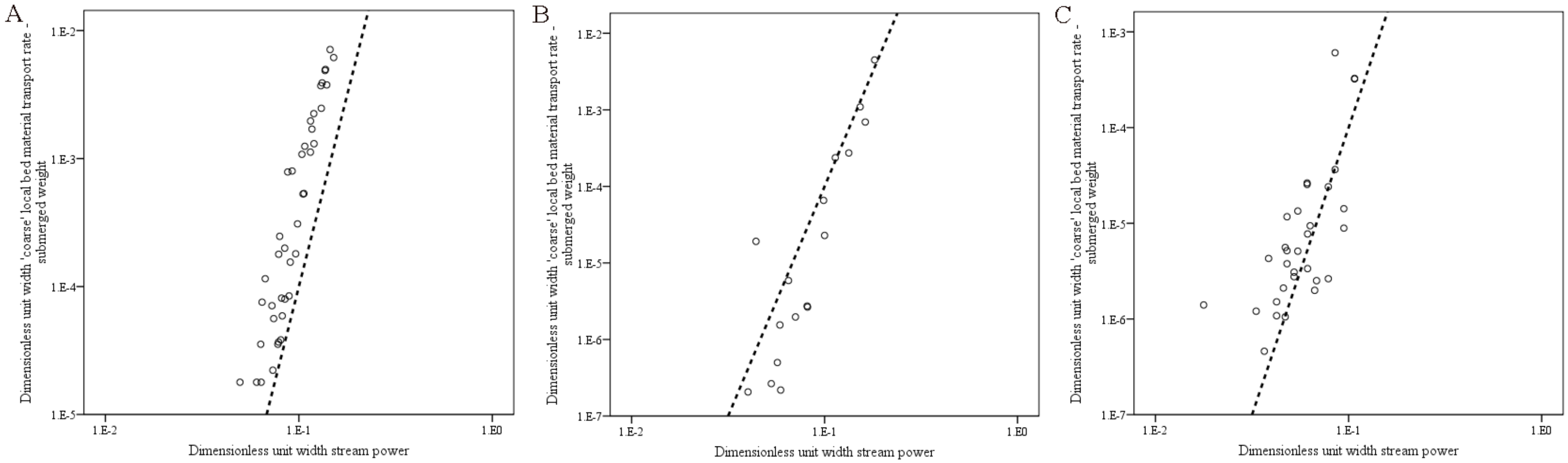


Figure 6.10 Examples of datasets within first (competence) phase of bed surface material transport. (A) Johnson's (1943) laboratory investigations on bed-load transportation, series V, taken from the Gomez and Church (1988) collection of data. (B) Paintal's (1971) laboratory investigations on bed-load transportation, series V, taken from the Gomez and Church (1988) collection of data. (C) King et al.'s (2004) data for the Boise River, Idaho. Dashed line represents derived first (competence) phase of bed surface material transport relationship.

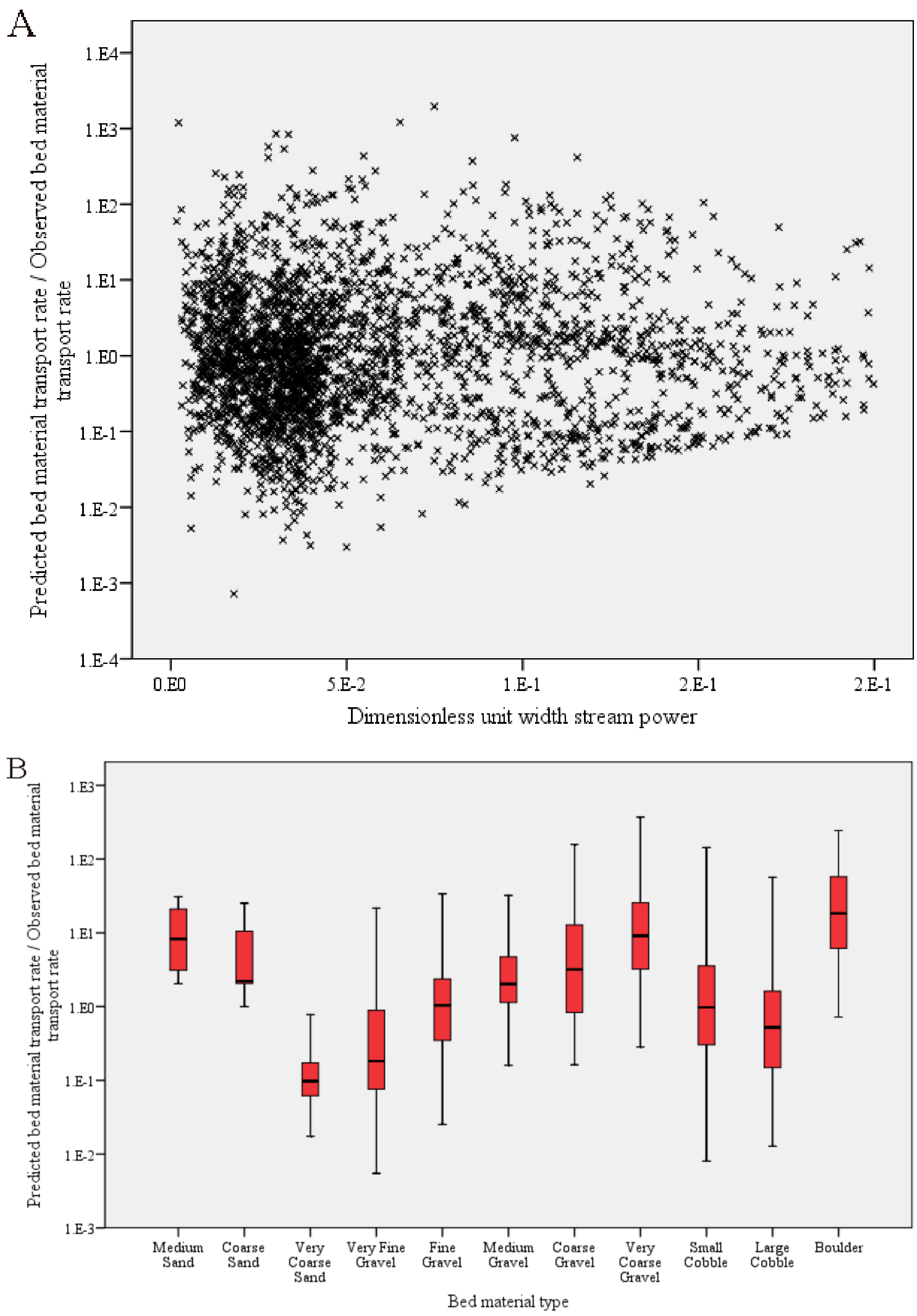


Figure 6.11 Ratio between predicted and observed values within first (competence) phase of bed surface material transport relationship. (A) Plotted against dimensionless stream power per unit bed area. (B) Plotted for different bed surface material types.

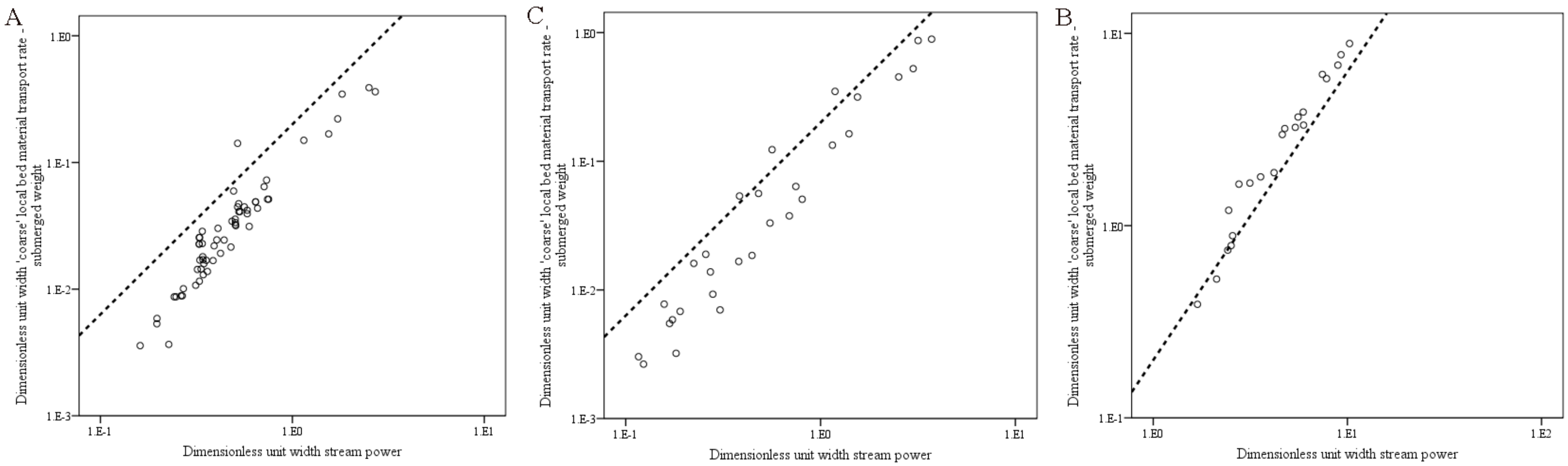


Figure 6.12 Examples of datasets within the second (capacity) phase of bed surface material transport. (A) Einstein's (1944) data for Mountain Creek, South Caroline, taken from Yang's collection of data (1979). (B) Gilbert's (1914) laboratory investigations on the transport of debris by running water, 0.305mm sand in a 1.32ft wide flume, taken from Yang's collection of data (1979). (C) Williams's (1969) laboratory investigations on the transport of coarse sand, taken from Yang's collection of data (1979). Dashed line represents derived second (capacity) phase of bed surface material transport relationship.

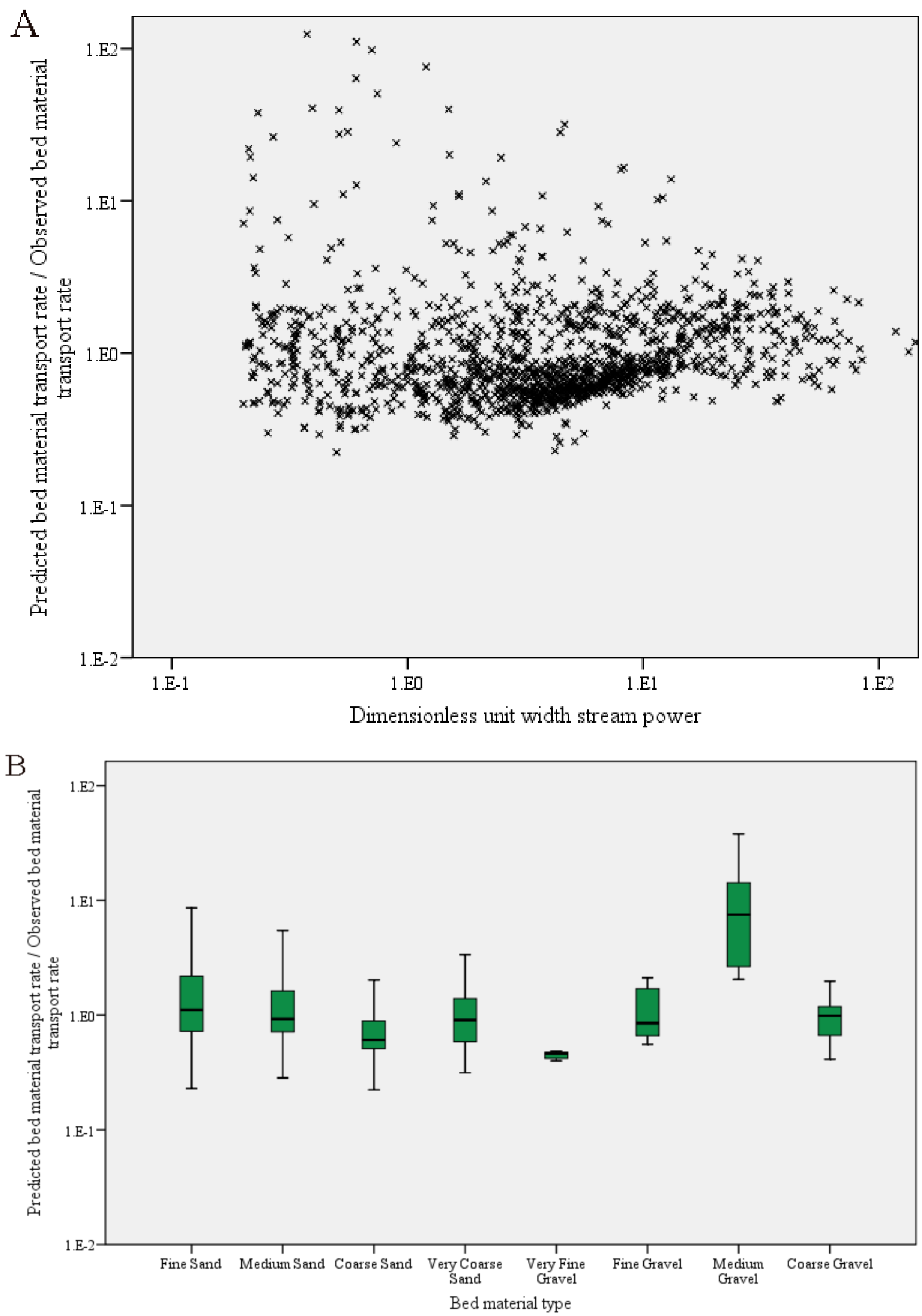


Figure 6.13 Ratio between predicted and observed values within second (capacity) phase of bed surface material transport. (A) Plotted against dimensionless stream power per unit bed area. (B) Plotted for different bed surface material types.

It could be argued that the two phases of the bed surface material transport apparent in Figure 6.8 and expressed in Equation 6.23 represent discrete and unrelated types of transport relating to different environmental conditions (for example, gravel versus sand-bed channels). To test this, datasets that had values of ω^* both below and above the apparent threshold value of 0.25 were identified. A selection of these datasets is displayed in Figure 6.14. It is evident, even within a single dataset, that crossing an approximate threshold of $\omega^* \approx 0.25$ results in an obvious change in the relationship between dimensionless stream power per unit bed area and dimensionless bed surface material transport rate.

As identified in Section 6.3.4, limitations to the supply of material can significantly affect the relationship between stream power per unit bed area and bed surface material transport. Figure 6.15 demonstrates how datasets known to be supply-limited (and which were not therefore included in the derivation of Equation 6.23) deviate from the bed surface material transport relationship derived for second phase transport, while datasets identified by Gomez (2006) as definitely having no supply limitations fall along the derived relationship.

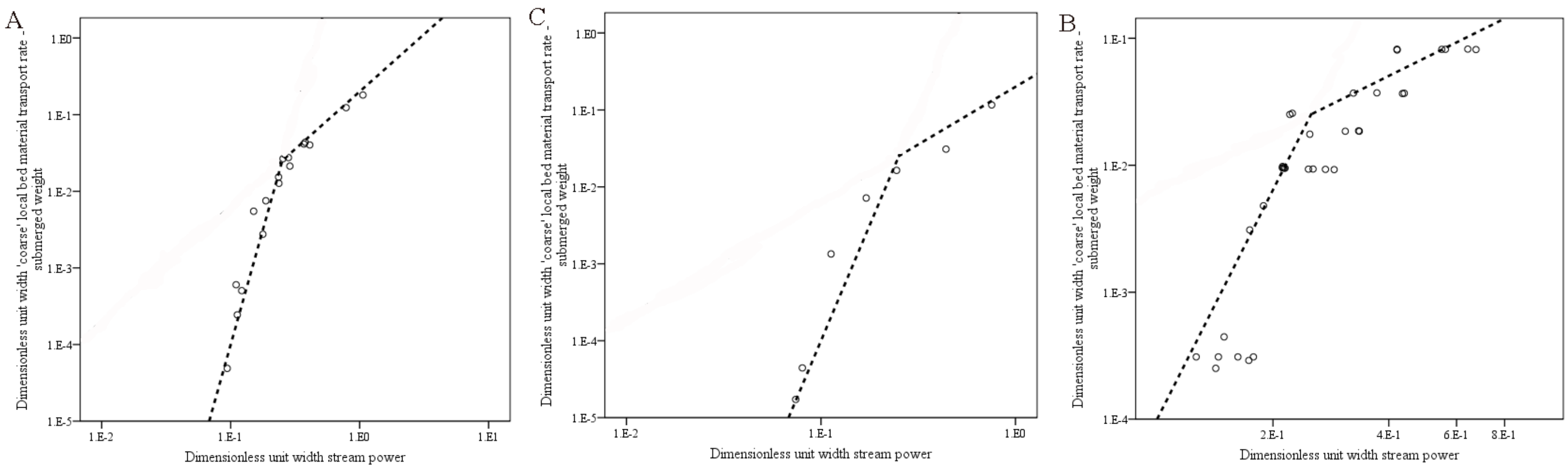


Figure 6.14 Examples of datasets that cross between the first (competence) phase and second (capacity) phase of bed surface material transport. (A) Ikeda's (1983) laboratory investigations on bed-load transport, taken from the Gomez and Church (1988) collection of data. (B) Meyer-Peter and Muller's (1948) laboratory investigations on bed-load transport, series 1, taken from the Gomez and Church (1988) collection of data. (C) Wilcock's (1987) laboratory investigations on bed-load transport of mixed-size sediment, 0.5phi series, taken from the Gomez and Church (1988) collection of data. Dashed line represents derived bed surface material transport relationship.

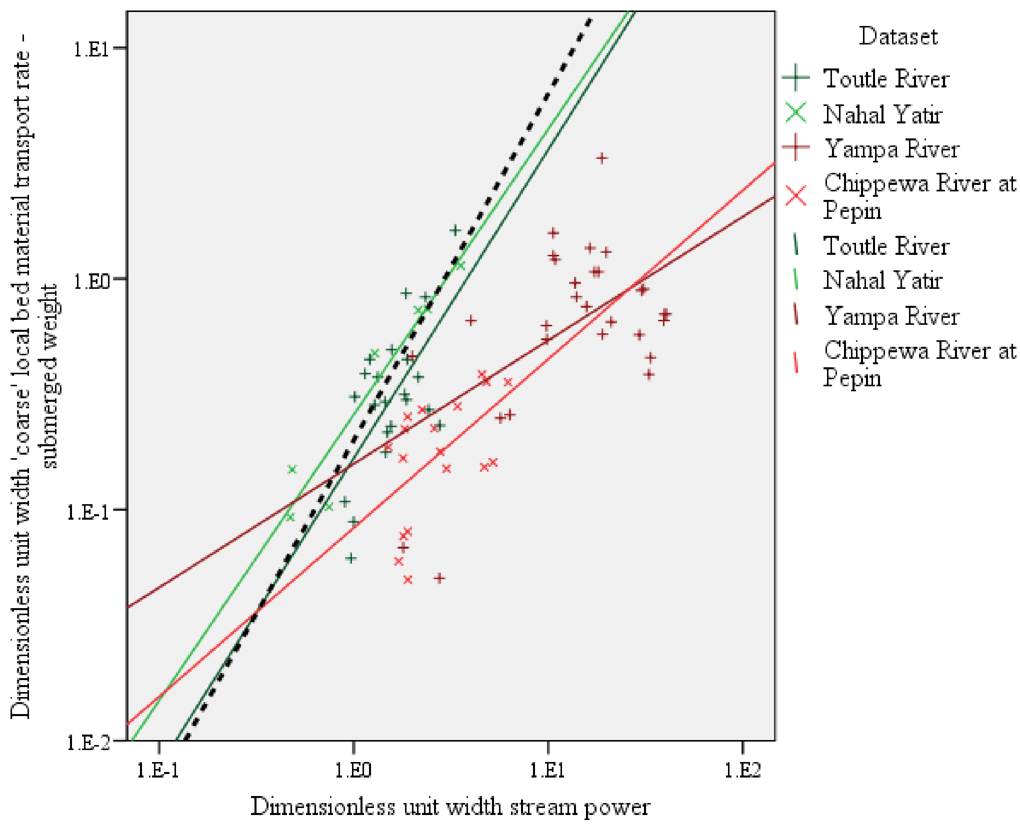


Figure 6.15 Demonstration of the difference in association between transport- (in green) and supply- (in red) limited datasets with the derived capacity phase of bed surface material transport relationship. Dashed line represents the derived capacity phase of the bed surface material transport relationship.

6.5 Discussion

6.5.1 Stream power per unit bed area as the flow parameter most appropriate for predicting bed-load transport rate

It is apparent from the results in Section 6.4.1 that, despite the case made for application of unit width kinetic power to sediment transport analysis, that parameter is not as strongly correlated with bed-load transport as some of the other parameters representing flow intensity.

More interesting however, is the finding that the association between tractive force and sediment transport rate is also weaker than those for the other parameters. Further, while mean flow velocity is nearly as strongly associated with sediment transport as stream power per unit bed area, it, like tractive force, is less consistent in its association than is stream power per unit bed area. The causes of the inconsistent associations that both mean velocity and tractive force display with transport rate have been the subject of much discussion in the historic literature, and yet are apparently neglected by contemporary approaches to sediment transport prediction.

Clifford (2008) provides a detailed review of the historic literature dealing with the physical complexities associated within the onset of sediment movement. This review offers a useful entry point for making sense of the substantial progress that has been made, but seemingly forgotten in this area. Meyer-Peter *et al.* (1934) were among the first to express dissatisfaction with formulae that incorporated either velocity or tractive force relations (such as du Boys, 1879). They considered such relations were unlikely to be valid, because the distribution of velocity and tractive force in a channel are non-uniform and vary with channel roughness. A recent investigation into the threshold of motion highlighted this non-uniformity and the impact that it has on the critical dimensionless tractive force (Shields parameter) at different slopes (Parker *et al.*, in review). Parker *et al.* identified that increases in slope act to increase the tractive force necessary to entrain sediment, whilst having an opposite effect on the critical mean velocity. Similarly, Rubey's (1938) consideration of the factors influencing the onset of sediment movement revealed that finer sediment entrainment appears to depend strongly upon shear stress but not on velocity, whilst the entrainment of larger sediment appears to be dependent on mean velocity, but not on shear stress. Finally, Brooks (1958) observed that, in flumes with flows of the same depth and slope (and therefore tractive force), sediment transport rates varied with mean velocity (caused by variations in slope and/or channel roughness). Therefore, transport equations based on tractive force fail to predict the multiple values found experimentally through variation in velocity.

The work of Rubey (1938) went someway to understanding why both tractive force and mean velocity are inconsistent in their predictions of bed-load transport rate for different values of channel slope and roughness. He argued that near-bed velocity is actually the parameter most appropriate for predicting the transport of bed-load but that, since it is a parameter that is difficult to define, measure or predict, tractive force and mean velocity are useful substitutes. Mavis and Laushey (1949) came to similar conclusions, emphasising the importance of near bed velocity on sediment transport. However, they suggested approximating near bed velocity by combining mean velocity and tractive force together. This line of argument was further pursued by Parker *et al.* (in review) when identifying the most appropriate means of defining the threshold of motion. They concluded that, because it has been shown empirically that critical velocity and critical tractive force both vary with slope (and relative roughness) whilst critical stream power per unit bed area does not, stream power per unit bed area is a more suitable parameter for defining the initiation of motion. The theoretical justification for this is that, because stream power per unit bed area is the product of tractive force and mean velocity, it essentially acts to combine their effects in a similar manner to that suggested by Mavis and Laushey (1949). It is argued here that it is the *combined* influence of both velocity and tractive force (Equation 6.6) that is responsible for stream power per unit bed area having such a strong association with sediment transport.

It is surprising that Yang's (1972) unit weight stream power is relatively poorly associated with sediment transport rate compared with stream power per unit bed area (and even mean velocity). It is apparent from examining Table 6.2 in detail that unit weight stream power performs similarly to stream power per unit bed area for flume-based datasets (where flow intensity is largely controlled by varying slope). However, it performs relatively poorly for field-based datasets (where flow intensity is largely controlled by varying discharge).

Within the 'Erosion and Sedimentation Manual' for the US Bureau of Reclamation, Yang (2006) argued that unit weight stream power is the most appropriate parameter for predicting bed-load. Using both Meyer-Peter and Muller's (1948) and Gilbert's (1914) flume datasets, Yang (2006) demonstrated that when sediment concentration is plotted against either tractive force or stream power per unit bed area a 'loop effect' is observed. This loop effect indicates that a range of tractive force or stream power per unit bed areas can be used to explain the same sediment concentration, while unit weight stream power and sediment concentration are correlated with each other far more consistently. However, Yang's (2006) argument is critically flawed because in it he compares how well all of the tested parameters correlate with sediment concentration, when only Yang's (1972) unit weight stream power is designed to predict sediment concentration – the others being better associated with unit width sediment transport rate. This important difference becomes apparent in the description of the difference between unit width and unit weight stream power in Section 6.3.2: Bagnold's stream power per unit bed area gives the rate of energy loss from water occurring over a *unit bed area* whilst Yang's unit weight stream power gives the rate of energy loss within a *unit weight of water* flowing over a bed. Therefore, clearly, Bagnold's parameter should be compared with the rate at which sediment is transported over a given area of the bed of the channel (unit width transport rate); whilst Yang's parameter should be associated with the amount of sediment carried within a unit of flowing water (sediment concentration). Examining Table 6.2 and Figure 6.4, it is apparent that when stream power per unit bed area and unit weight stream power are both correlated against their appropriate transport variables, stream power per unit bed area has the strongest association.

Alongside its conceptual attractiveness and empirical efficacy, one final major factor that contributes to the appeal of stream power per unit bed area as a parameter for predicting sediment transport is that it is pragmatically convenient in its application. Ferguson (2005) describes how stream power per unit bed area can be approximately calculated from gross channel properties (width and slope), together with the discharge provided by the catchment, without needing to know within-channel flow properties such as depth or velocity. Values for discharge, width and slope can be derived using nationally available datasets, while depths (necessary for the calculation of shear stress) are dependent on local channel roughness, which is difficult to parameterise. Section 6.6 explores how each of the three parameters needed to represent stream power per unit bed area can be derived at the catchment-scale across British rivers.

6.5.2 The problem of supply limitations

Even after the data filtering process described above (Section 6.3.4), there is still a significant proportion of variability within the remaining bed-load transport datasets that is not accounted for by flow intensity. Errors in both measured bed-load transport rates and calculated stream power per unit bed area values mean that, even if a transport dataset is truly transport-limited, the association will likely be less than 100%. However, there is no objective basis for identifying how far below 100% the correlation can sink before the dataset should be classed as not being 'transport-limited'. Beyond the arbitrariness in the selection of 0.75 as a discriminant of transport-limited status, it should also be noted that, even if variations in the transport rate observed within a study reach correlate closely with the variations in the flow's capacity to transport, the study reach may still be supply-limited in circumstances where the transport rate is actually controlled by the supply of material from upstream, which is itself strongly associated with the (downstream) reach's transport capacity. Further, supply-limitations are not only spatial phenomena. Temporal variations in sediment supply have been recognised as common features of coarse material transport under both quasi-steady (Hoey, 1992), and variable (Reid *et al.*, 1985) flow regimes. Sediment pulses have been linked with a variety of mechanisms, but the migration of coherent bed forms is considered by some to be the most prevalent cause. As dunes pass a given point maximum amounts of transport are associated with the passage of dune peaks and smaller amounts with that of intervening troughs (Leopold and Emmett, 1976). Similarly, low-amplitude, bed-load sheets formed from the migration of heterogeneous, coarse sediments can also produce pulses (Whiting *et al.*, 1988). These temporal variations in sediment supply may result in bed-load measurements from a generally transport-limited site being supply-limited transport at certain times.

The only means of completely controlling for the influences of the complexities involved in the quantity and calibre of material available for transport is to perform experiments under laboratory conditions. But then, within laboratory flume experiments, it is difficult to fully replicate the processes occurring in natural river channels. Whatever the limitations of the data filtering and adjustments made, the relationship displayed in Figure 6.8 is clearly representative of transport-limited conditions, since the datasets taken from Gomez (2006) known to be completely transport-limited, fall along the derived curve, whilst datasets considered to be supply-limited do not (Figure 6.15).

6.5.3 Multiple-phases of coarse material transport

Section 6.3.5 described how many studies have referred to bed-load transport in rivers occurring in multiple phases. These have been summarised and schematised by Barry (2007) in his thesis on bed-load transport and are reproduced in Figure 6.16. Barry (2007) describes bed-load transport as occurring in up to three phases, although by far the most commonly cited are Phases I and II. Based on the descriptions of Phase I and II transport given in Section 6.3.5, it is considered here that, by using only the fractions of bed-load representative of the bed surface material, the sediment transport relation displayed in Figure 6.8 and described by Equation 6.23 has effectively ignored what is commonly referred to as Phase I transport. This is because the sediment fractions transported within Phase I transport are not well represented on the bed surface, but instead are sourced from upstream sources, channel margins and slack flow areas.

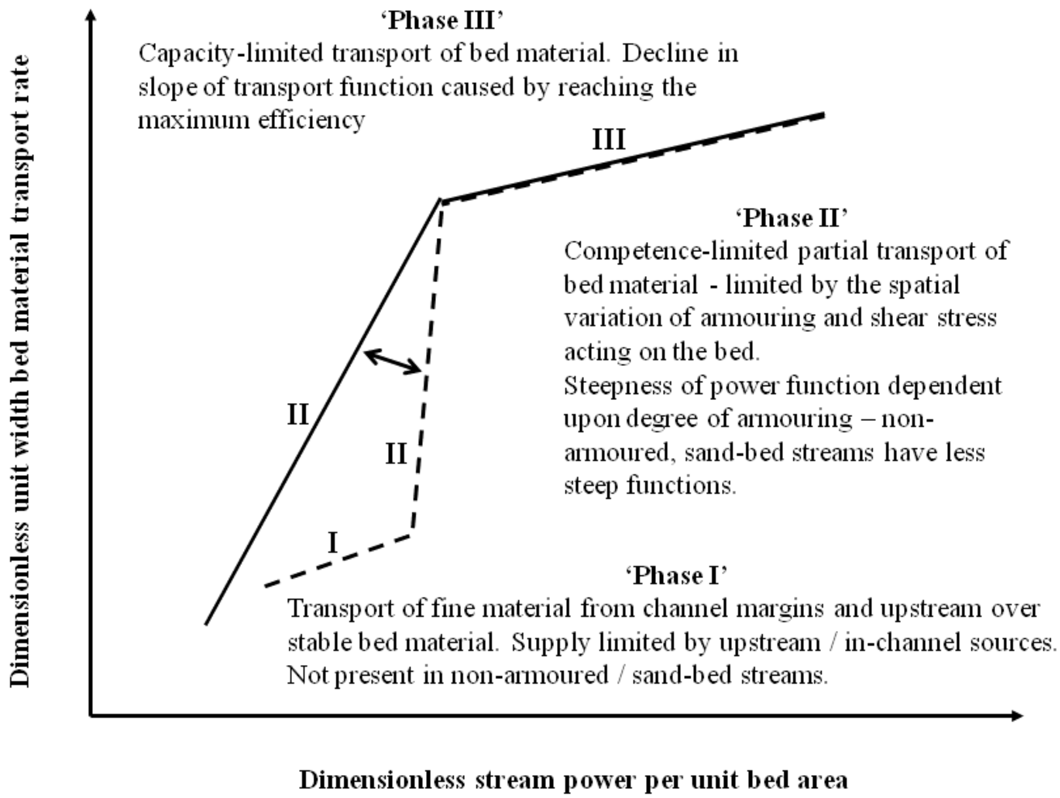


Figure 6.16 Schematic illustration of the phases of bed-load transport possible in non-armoured (solid lines) and armoured (dashed lines) channels. Modified from Barry (2007).

The transition between Phase I and Phase II transport is thought to be at or near the bankfull flow (Jackson and Beschta, 1982; Parker *et al.*, 1982; Andrews, 1984), but this threshold is often poorly defined (Ryan *et al.*, 2002). In gravel-bed streams, the surface particles are large enough that they will not be mobilised until moderate to high flows (Wilcock and Kenworthy, 2002). Conversely, in non-armoured, sand-bed streams the sediment particles will typically be mobilised even during low flows (Figure 6.16). As the flow intensity increases under Phase II transport conditions, more of the surface grains are entrained and expose more of the subsurface material to the flow, providing additional sources of sediment for transport (Barry, 2007). The relatively rapid increase in sediment transport rate associated with this phase of transport is likely to continue in both armoured and non-armoured channels as existing sources of sediment are further accessed and new sources of sediment are mobilised with increasing discharge (i.e. sediment sources higher up on the channel banks or from new areas of the channel bed as the spatial extent of excess shear stress expands).

Based on this description of Phase II transport, it is considered here that it corresponds to the first phase of transport observed in the bed surface material transport relation displayed in Figure 6.8 and described by Equation 6.23 (i.e. the bed surface material transport when $\omega^* < 0.25$). This phase of bed surface material transport is limited primarily by the ability of the flow to entrain the bed surface particles. During this phase the bed can be considered to be under partial transport conditions (Haschenburger and Wilcock, 2003) – where certain grains on the bed surface remain immobile while others are transported. This may either be due to the size of the grains, or the nature of the 'patch' which they sit within. As flow intensity increases areas of partial transport become larger at the expense of inactive areas and a more developed stage of 'Phase II' transport is reached. Gilbert (1914) identified the ability of the flow to entrain the bed surface particles as an important control over the rate at which sediment is transported, and termed it the 'competence' of the flow. To avoid semantic confusion arising from defining the first phase of the bed surface material transport relationship displayed in Figure 6.8 as Phase II, this phase of transport is referred to here as the 'Competence Phase' of bed surface material transport.

It is hypothesised here, that the scatter around the function displayed in Figure 6.8 is due to the local conditions governing sediment entrainment of bed surface material particles. One major influence over the entrainment of sediment grains is the armouring of bed surfaces. Therefore the nature of the Competence Phase (Phase II) transport relationship is a function of the degree of channel armouring as it regulates the supply of surface and subsurface material. Barry (2007) described how poorly-armoured channels are expected to have lower-sloped Competence Phase curves than well-armoured ones (Figure 6.16). In well-armoured channels, mobilisation of the coarse armour layer is delayed (armour break-up occurs at higher flows) relative to a poorly-armoured channel (armour break-up occurs at lower flows) and, consequently, is followed by a larger increase in bed-load transport rate than would occur in a similar channel with less surface armouring (Barry, 2007). Movement of the armour layer exposes the subsurface supply, causing a rapid increase in transport rate and the steep Competence Phase transport relationship (Figure 6.16) typical of many gravel-bed streams (Jackson and Beschta, 1982). In the case of a non-armoured channel, the onset of Competence Phase transport begins at very low flows due to the low flow intensities required to mobilise the relatively fine surface sediment.

Other than the commonly referred to Phase I and Phase II (Competence Phase) transport, Barry (2007: 127) also suggested the presence of Phase III transport, where he described the decline in the order of the transport power function at high flows as "a decline in the slope of the transport function". Whilst this third phase was not observable in the data Barry obtained from Oak Creek (2007: Figure 3.4) there was an observable decline in the order of the transport relationship within the bed-load data he obtained for the East Fork River (2007: Figure 3.4). This third phase is apparent in Figure 6.8, and corresponds to the transport function for dimensionless stream power per unit area values equal to or greater than 0.25 ($\omega^* \geq 0.25$).

Barry (2007) suggests a number of potential causes for this Phase II/III transition including: (i) the flow reaching its maximum efficiency and therefore transporting sediment at its maximum capacity; (ii) the flow reaching bankfull stage, so that additional discharge spreads across the floodplain rather than continuing to increase transport rate; and (iii) all available sediment sources having already been accessed by the flow, such that further increases in discharge do not result in large increases in transport. It is theorised here that the first of these explanations is the most likely based on the observations made during this study. First, it is known that the transition from Phase II to III transport does not occur at bankfull discharge within many of the datasets used to construct Figure 6.8, most notably because they are flume data. Further, Barry (2007) also describes the Phase II/III transition as occurring at 25% of bankfull within his East Fork River dataset, negating the influence of out of bank flows. Secondly, it is known that some of the datasets used to construct Figure 6.8 have a near infinite supply of sediment made available to them, not only in the case of flume studies, but also the datasets identified by Gomez (2006) as lacking any supply limitations (Figure 6.15). Therefore, the decline in the order of the transport function observed initially by Barry (2007), and confirmed in Figure 6.8 cannot be due to either the inefficiency of out of bank flows or limitations on the supply of material, but is instead likely caused by the flow being limited by its transport capacity – at a given stream power all of the energy available for transporting sediment is being used. On this basis, this final phase is referred to here as 'Capacity Phase' transport. It is noted here that the decline in the order of the transport function illustrated in Figure 6.8 does not indicate that arithmetic increases in transport rate with stream power are declining – absolute increases in transport rate may still be increasing, just at a reduced rate.

In summary, it is theorised that an increase in stream power within Phase II / competence-limited transport results in an increase in transport rate *via* an increase in the proportion of the bed that can be entrained, and that the transport rate is limited by the ability of the flow to entrain all components of the bed rather than the maximum transport efficiency of the flow. Theoretically, the Phase II/III transition represents the point at which, despite having the competence to entrain plenty of new material from the bed, the flow does not have the capacity to transport it all because of a limit to the efficiency with which it can use its available energy. Within Phase III / capacity-limited transport it is theorised that an increase in stream power results in an increase in the transport rate *via* an increase in the capacity of the flow, and that the transport rate is limited by the maximum transport efficiency of the flow rather that the ability to entrain any particular component of the bed. However, despite the flow operating at its maximum transport efficiency during capacity-limited transport any increase in stream power still results in a nonlinear increase in transport rate because of the increased rate at which energy is made available.

One reason why Phase III / capacity-limited transport is not commonly referred to is that it is relatively rare within natural streams. By the definition given above, capacity-limited transport involves the mobilisation of the entire stream bed. Therefore, any stream beds experiencing capacity-limited transport on a regular basis would be extremely unstable. Instead, natural stream bed surface material is commonly large enough to avoid capacity-limited transport under all but the most extreme flows. This is supported by field evidence from the literature: during their documentation of partial transport in Carnation Creek in British Columbia Haschenburger and Wilcock (2003) found that even a flood with a seven year return period had insufficient power to entrain the entire bed.

An important limitation of the transport relationship illustrated in Figure 6.8 and described by Equation 6.23 is that it is a *bed surface material* transport relationship. Isolating the bed surface material from the potentially supply limited finer fractions did make it easier to define a generally consistent relationship but it does mean that the transport relationship derived ignores all material finer than that observed on the bed surface and therefore is actually just for bed surface material – not for bed-load or even bed material. Whilst this limitation should be taken into account during its application, it should not inhibit the intended function of the derived transport relationship – which is a generally applicable formula that provides indicative, not absolute, predictions of sediment transport capacity.

6.6 Parameterising the variables used to calculate reach sediment transport capacity

6.6.1 Introduction

The remaining objective of this chapter is to describe how the general bed surface material load relationship developed here can be applied in British rivers so that it can be used within the new reach-based sediment balance approach. The four variables necessary to calculate a bed surface material transport rate using Equation 6.23 are: discharge, slope, width and bed surface material size. Approaches to obtaining values for each of these input variables are identified based on the review of data sources and techniques in Chapter Three.

6.6.2 Discharge: estimating the annual flow distribution curve

It was concluded in Section 3.2.1 that it is preferable to incorporate the complete flow distribution into any treatment of river sediment dynamics since single representative flows like the dominant or effective discharge can fail to represent the effect that the full range of flows has on sediment transport (Doyle and Shields, 2008). Further, it was identified in Section 3.3.5 that the most appropriate geomorphological time-scale over which to apply a reach-based sediment balance approach is that referred to as 'steady-state' time. This refers to the temporal scale at which local changes in channel morphology are observable, but there are no significant changes to those variables treated as independent within this approach (channel slope, width and flow discharge). It is also the temporal scale of most interest to contemporary river scientists and practitioners as it is identifiable on an anthropogenic level (1-100 years). Therefore, the reach-based sediment budget, or CSR approach, employed in this thesis is based on the annualised quantity of bed surface material load transported by the average annual flow distribution.

Because it was not possible to apply 'Low Flows 2000' due to licensing restrictions, an alternative approach to representing flow duration curves at ungauged sites has been developed for application within a reach-based sediment balance approach.

This alternative approach is informed by the procedures of 'Micro Low Flows' (Young *et al.*, 2000), Low Flows 2000's predecessor and utilises the readily available data sources described in Section 3.2.1. The modified Low Flows approach is based on a simple conceptual water balance model for estimating mean annual flow (Q_{MAF}), and a statistical multivariate model for estimating the standardised flow exceeded 95% of the time (Q_{95}). Based upon these two parameters, it is possible to approximate a flow duration curve for any ungauged site. The overall estimation procedure is presented schematically in Figure 6.17 and the individual stages are briefly summarised here. The mean flow at an ungauged site is estimated using a simple conceptual water balance model. The climatic variables used are derived from digitised versions of the 1:625,000 Meteorological Office standard period average annual rainfall (SAAR - NERC, 1975) and the 1:2,000,000 average annual potential evaporation (PE - Grindley,

1970) maps. The average annual runoff depth (AARD), in millimetres, is derived using a simple water balance given by:

$$AARD = SAAR - (r \cdot PE)$$

Equation 6.24

where,

$$r = \begin{cases} (0.00061 \cdot SAAR) + 0.475 & \text{for } SAAR < 850\text{mm} \\ 1 & \text{for } SAAR \geq 850\text{mm} \end{cases}$$

Equation 6.25

The scalar, r, reflects the impact of soil moisture deficit and associated reductions in evaporation rates observed in lower rainfall catchments (Young *et al.*, 2000). The mean annual flow at the ungauged site (Q_{MAF}) is estimated by rescaling AARD by the catchment area.

Previous analysis of British gauged flow records has demonstrated a strong relationship between Q_{95} and the gradient of the FDC (Gustard *et al.*, 1992). Young *et al.* (2000) describe a statistical multivariate regression model which derives a standardised Q_{95} from the hydrological characteristics of soils within gauged catchments. Within the UK, the hydrological characteristics of soils are represented by the Hydrology Of Soil Types (HOST) classification (Boorman *et al.*, 1995) which are grouped by hydrogeological and low flow response similarity into 11 Low Flow HOST groups (LFHG) and one additional group, LFHG12, representing the areal extent of lakes.

Based upon the standardised Q_{95} value identified using the multivariate regression model, a standardised flow duration curve is selected from a family of type curves. These type curves are illustrated in Figure 6.18 and were derived by pooling standardised curves from the study catchments by Q_{95} class (Young *et al.*, 2000). However, as the original methodology developed by Young *et al.* (2000) is concerned with deriving flow duration curves specifically for low flow conditions, their curves are only described up to the Q_2 (the flow exceeded 2% of the time).

As coarse sediment transport is known to be largely driven by larger, less frequent flows (Wolman and Miller, 1960), it was necessary to extrapolate the curves described by Young *et al.* (2000) using polynomial functions so that the FDCs incorporate flows up to the $Q_{0.01}$ (the flow exceeded 0.01% of the time).

The type curves adjacent to the estimated value of Q_{95} are identified and a standardised FDC that coincides with the predicted value of Q_{95} is generated by linearly interpolating between these curves. The final step in the estimation procedure is to re-scale the flow duration curve by the estimated value of mean flow. Based on values for catchment area, annual potential evaporation, annual rainfall, and HOST groups obtained from the data sources described in Section 3.2.1, FDCs are derived every 50m along the channel throughout the catchment network.

Young *et al.* (2000) demonstrated the predictive performance of their mean flow and annual Q_{95} models graphically in their Figure 4. The factorial standard error for their mean flow model is 22% which approximates to a 68% confidence interval for the model's predictive capacity of 22% of the observed value, whilst those for the standardised Q_{95} model are approximated as 7.4% of the mean flow (Young *et al.*, 2000). It is assumed that similar levels of accuracy apply to the mean flow and annual Q_{95} models derived here since they have been developed using the same methodology and datasets.

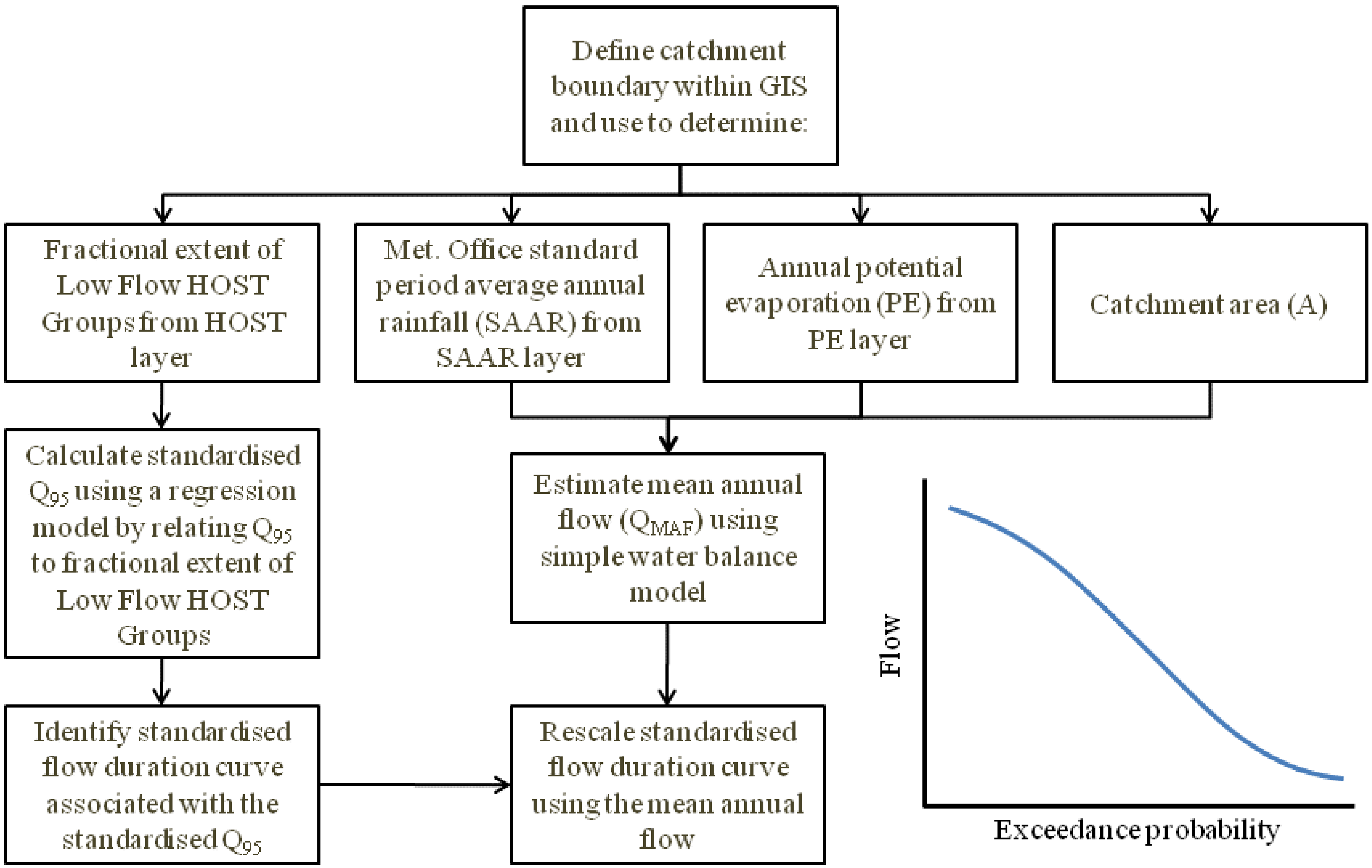


Figure 6.17 Procedure for estimating the flow duration curve of an ungauged catchment using a modified Low Flows methodology (modified from Young et al., 2000).

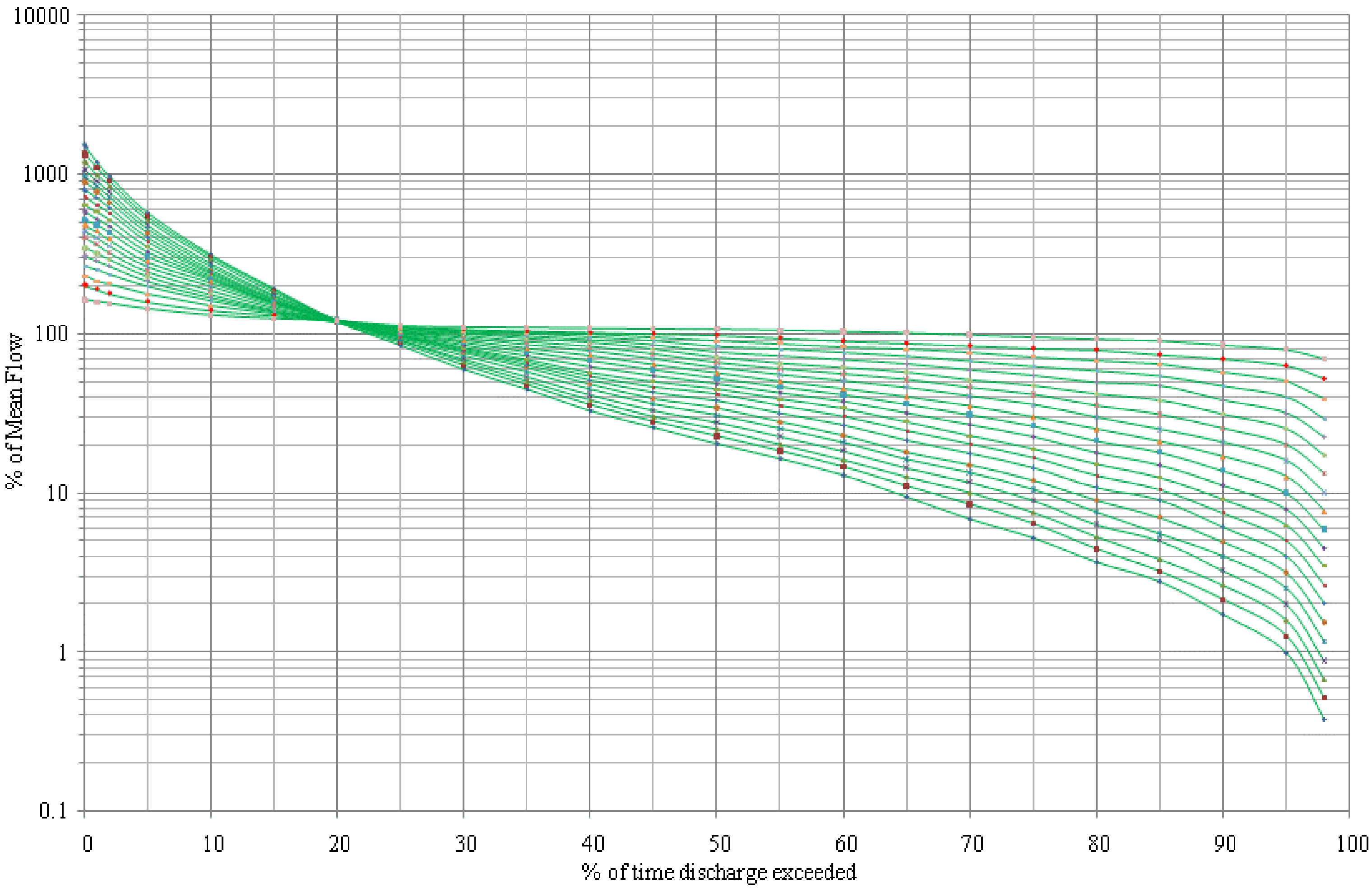


Figure 6.18 Examples of predicted non-dimensional flow duration curves for catchments of varying geologies.

6.6.3 Slope

Section 3.2.3 evaluated a selection of different sources of elevation data and different techniques for calculating slope. Based on this evaluation, and a consideration of the needs of the reach-based sediment balance approach described in Chapter Four, an overlapping horizontal slice slope calculation method has been employed. This technique prevents the 'loss' of important local changes in slope, whilst maintaining a consistent horizontal measurement length, factors which have made it popular with other studies (Jain *et al.*, 2006; Barker, 2008). Slope values are derived every 50m along the stream line, and overlap across a somewhat arbitrarily chosen horizontal slice length of 250m. This slice length is shorter than that applied by Barker (2008), as his study was focused on representing general trends in downstream stream power and so was less concerned with local imbalances in sediment transfer. High horizontal resolution and vertical accuracy DEMs such as LiDAR and IfSAR are recommended as elevation data sources from which to measure slope. Less accurate elevation data sourced from the OS Landform Profile DTM is unsuitable because of elevation 'steps' that are artefacts left over from their interpolation from contour data.

6.6.4 Width

Section 3.2.2 identified OS MasterMap river channel polygons as the only source of channel width data of sufficient accuracy and coverage for the purposes of this study. Alongside the discharge and slope values described above, channel widths are measured from OS MasterMap river channel polygons every 50m throughout the river network.

6.6.5 Bed surface material size

Section 3.2.5 identified that there are no datasets available that provide reliable representations of bed surface material size with sufficient national coverage to be useful to the aims of this thesis. Section 4.5 argued that it was reasonable to treat bed surface material size as a dependent variable in the context of a uni-directional, steady-state representation of catchment-scale coarse sediment dynamics and concluded, therefore, that bed surface material size must be taken as being uniform for all reaches in the fluvial system. However, it is still necessary to choose an appropriate bed surface material size to be applied uniformly throughout the study catchment. For the purpose of applying the new reach-based sediment balance approach, the uniform grain size chosen for each model is the modal bed surface material type reported in the RHS database for sites located in the modelled catchment.

Chapters Four, Five and Six have described the details of a new reach-based sediment balance approach for accounting for coarse sediment dynamics in British rivers. The following chapter will introduce the completed approach and assess its performance within two test catchments.

Chapter Seven: Model assessment – evaluating the outputs of ST:REAM, a reach-based sediment balance approach to accounting for catchment-scale sediment dynamics in British Rivers

7.1 Methodology applied in the reach-based sediment balance approach

Section 4.1 identified the areas of investigation necessary to develop a reach-based sediment balance approach that could be applied widely throughout British rivers at the catchment-scale. The remainder of Chapter Four, and both Chapters Five and Six have focussed on answering the questions raised by Section 4.1 and Figure 4.1. It is now possible to produce a figure, similar to that in Figure 4.1, which summarises the answers to the questions raised (Figure 7.1). Based on these developments it has been possible to satisfy the first half of the research mission set out in Section 1.2: *"to develop … a new approach for quantitatively accounting for catchment-scale sediment dynamics in British rivers"*.

The new approach is termed '**ST**:**REAM**', '**S**ediment **T**ransport: **R**each **E**quilibrium **A**ssessment **M**ethod'. A copy of the latest working version of the model (Version 5) is provided in Appendix B, and a simplified schematic illustrating the procedures involved in performing a ST:REAM analysis is set out in Figure 7.2. The model currently sits within a Microsoft Excel 2003 workbook that contains three worksheets: 'Model Input', 'Model Data' and 'Model Output'

The first, 'Model Input', worksheet contains nine columns where the user is invited to input: the branch number, segment number, downstream branch number, downstream segment number, segment length, segment Q_{MAF}, segment Q_{95}, segment slope and segment width for each of the segments within the catchment. For clarity, segments are the units of channel length that the model later groups into reaches. Branch numbers are assigned based on increasing channel length – so that the main stem (longest length of channel from the mouth) is Branch 1, its longest tributary is Branch 2 and so on. Segment numbers are assigned from upstream to downstream. Segment length is user defined but it is recommended that the default value of 50m is applied uniformly. Segment Q_{MAF} and Q_{95} are identified by the user using the methodology described in Section 6.6.2. Segment slopes and widths are identified by the user using the methodologies described in Section 6.6.3 and 6.6.4 respectively. Before inputting the model data the user must also select a bed surface material size that is representative of the catchment, and a value of R to define the sensitivity of the reach boundary hunting algorithm. The bed surface material size should be based on the modal bed surface material class identified from RHSs in the catchment. The value of R is user defined but it is recommended that the default value of 0.01 is applied for the initial run and then adjusted for future model runs based on the scale of the user's investigation.

Once all of these values have been entered, the user presses the 'Input Model Data' button which starts a series of Visual Basic modules that divide each branch into a series of functional reaches on the basis of predicted sediment transport capacity. For each segment of each branch in the catchment the predicted bed surface material transport capacity at the mean annual flow (Q_{MAF}) is calculated using the sediment transport function derived in Chapter Six. Then the zonation algorithm described in Chapter Five is used to divide each branch into reaches with relatively homogenous sediment transport capacity values. Once the reach boundaries have been identified, the Q_{MAF}, Q_{95}, slope and width values from segments across each reach are averaged to define the appropriate values for each reach. The segment and reach values for each branch can be viewed by the user in the second, 'Model Data', worksheet.

Once the user has examined all of the reach-based data for the model an optional step is to identify reaches that have entirely unerodible boundaries (e.g. culverted). This is done on the third, 'Model Output', worksheet. When this has been completed the user clicks on the 'Run Model' button which begins a second series of Visual Basic modules that calculate the integrated annual bed surface material transport capacity for each reach on each branch of the catchment. First, the averaged annual flow duration curve for each reach is calculated using the reach's Q_{MAF} and Q_{95} values and the methodology described in 6.6.2. Then the submerged weight of material transported in each flow class of the flow duration curve for each reach is calculated using the bed surface material transport capacity derived in Chapter Six. From these values, the total annual bed surface material transport capacity is calculated for each reach. For reaches where the channel boundaries have been identified as non-erodible the total annual bed surface material transport capacity is limited by a maximum value equal to the capacity of its upstream neighbour(s) / its supply. Finally, the capacity supply ratio for each reach is calculated by dividing the annual transport capacity of the reach by the annual transport capacity of its upstream neighbour(s). Data and graphs of the supply, capacity and balance for each reach of each branch can be viewed on the third, ‘Model Output’, worksheet.

To complete the second half of the research mission it is necessary to establish that ST:REAM is a practical, but scientifically robust means of accounting for catchment-scale sediment dynamics in British rivers. This is the research challenge addressed in this chapter.

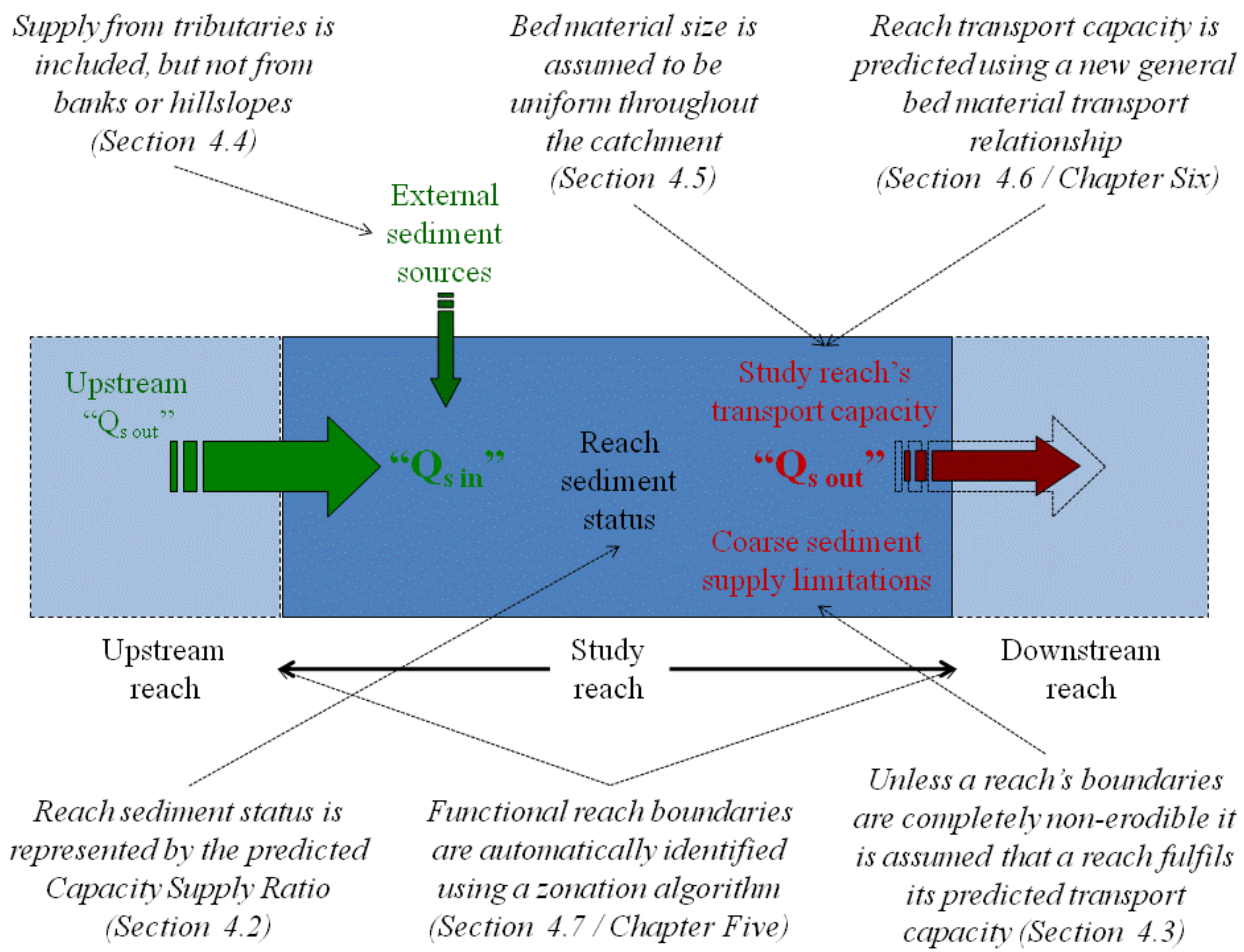


Figure 7.1 Framework for the ST:REAM reach sediment budgeting approach.

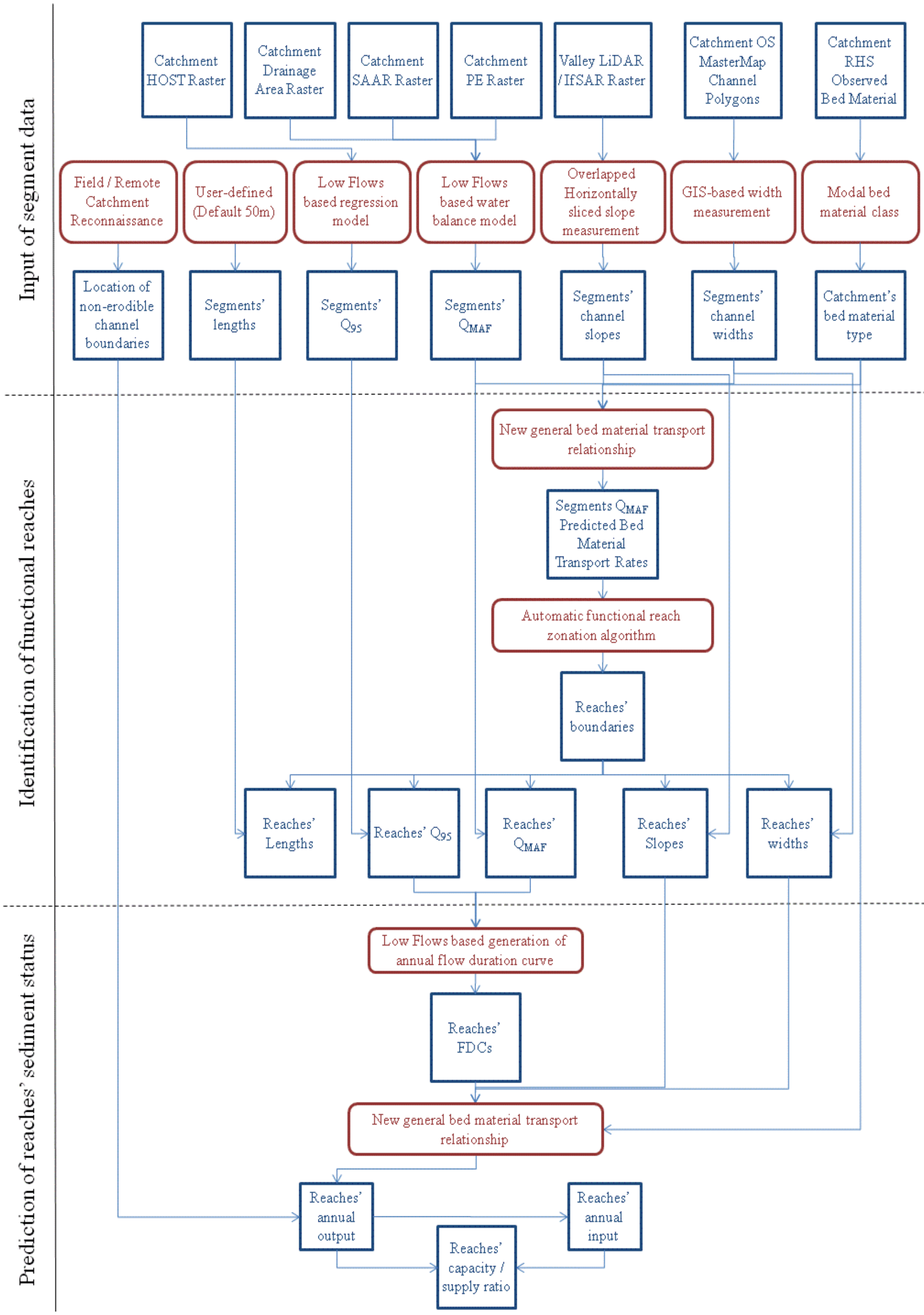


Figure 7.2 Schematic of procedures behind application of ST:REAM.

7.2 Model assessment versus model validation

The inherent uncertainties of models have been widely recognised, and it is now commonly acknowledged that the term 'validation' is an unfortunate one, because its root – valid – implies a legitimacy that we may not be justified in asserting.

(Oreskes and Belitz, 2001: 21)

Two terms that are often (incorrectly) used interchangeably in numerical modelling studies are: 'validation' and 'verification'. Verification is often used when testing that a piece of computer code is accurately solving model equations. Validation generally involves demonstrating that a model is a satisfactory representation of reality. However, as noted by Oreskes and Belitz (2001) in the opening quote, use of the term validation is misleading as it implies that a validated model, has legitimacy: that is it accurately represents reality, and, therefore, provides a *valid* basis for decision making.

Lane and Richards (2001) argued that it is philosophically impossible to 'validate' a theoretical model as no amount of empirical testing can ever cover all possible situations in time and space, and thus guarantee that the model will perform adequately outside the range of observed conditions or events. This is consistent with the Popperian view that models can never be proven, but only falsified, but Lane and Richards (2001) also raised issues concerning the practical utility of model falsification. These issues stem from the level of complexity in models of environmental systems, which is sufficiently high that falsification can be considered as:

i. inevitable, given not just the complexity of the real world that is being modelled, but also indeterminacy in many of its processes and the equifinality of many of its outcomes (Beven, 2002);
ii. dependent upon what criteria are set as necessary for falsification; or,
iii. of no real use unless it can inform the modeller of exactly *why* the model is failing.

Recognising the difficulties with validation and falsification, Lane and Richards (2001) attempted to identify better processes and terminologies with which models could be tested for success in order to ensure that they are used appropriately and improved progressively during practical applications. They conclude that ‘validation’, which implies perfection, truth and finality, is inappropriate and a broader term – ‘assessment’, is necessary because it is richer in content and implies an ongoing process. The use of ‘assessment’ when investigating model performance is also useful because it indicates that the success of a model depends to a degree on the perspective of the ‘assessor’. For example, different ‘assessors’ may have divergent views concerning what constitutes an acceptable success criterion. Further, the impossibility of either complete validation and falsification means that observational evidence alone is not sufficient to quantify model success. Variability between observations and predictions will always remain a significant part of the scientific research process. Therefore, progress comes not from determining the predictive success of a model, but more from understanding how and why a model fails. As a result, model assessment is a heuristic, evolutionary process concerned with establishing the domains of predictive success, and extending those domains through model development (Oreskes *et al.*, 1994). Model prediction failures can increase both methodological and substantive understanding: they can play a methodological role in improving model performance; and a substantive role in identifying the components of the model (and perhaps of the natural world) that influence outputs.

This more relaxed concept of model assessment may challenge the conventional, positivist approach to validation, but aspects of positivism may still be usefully incorporated into the approach. The use of independent observations is useful in ensuring that critical questions are asked of models. Inevitable divergences between model results and expected or observed values provoke consideration of their causes. This should lead to improvements in either: the model’s theoretical basis; the mathematical representation of the theory; the numerical coding; or the parameterisation of model inputs. The only other alternatives, which have already been identified above as theoretically unlikely/impossible are the complete rejection of the model (model falsification) and the complete satisfaction with the model (model validation). The nature of this heuristic assessment process is illustrated in Figure 7.3.

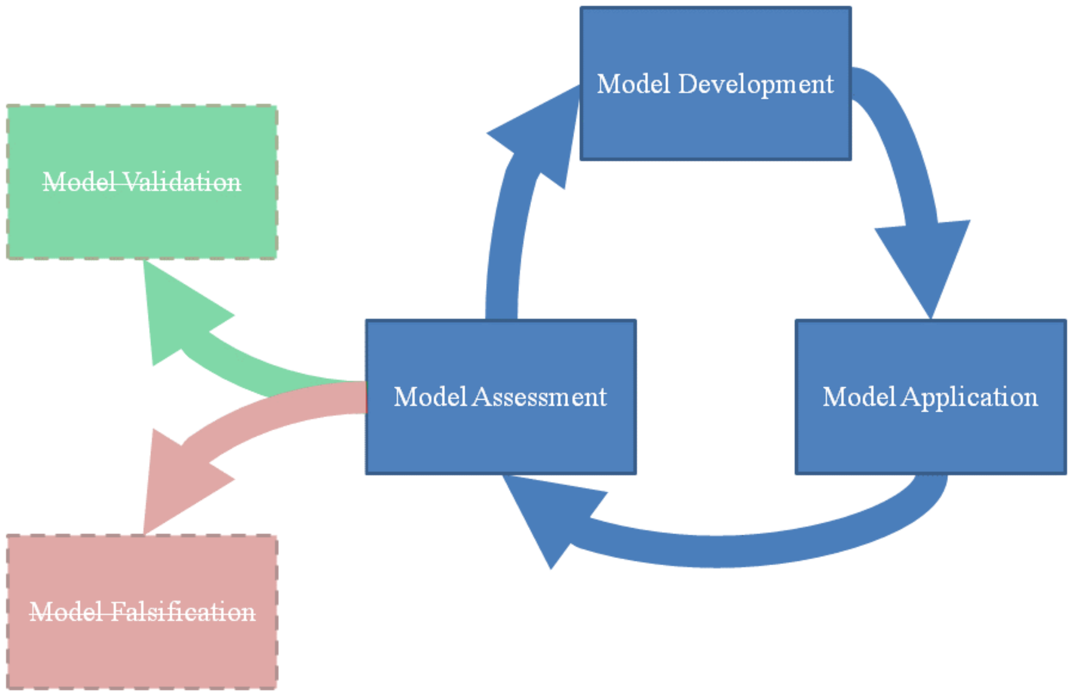


Figure 7.3 Conceptual representation of the model assessment process. Model validation and falsification have been intentionally faded to represent their improbability of occurrence.

The remainder of this chapter is informed by the philosophical issues discussed above, and in more detail by Lane and Richards (2001) and others, in its attempt to measure the 'success' of ST:REAM as a modelling tool. Therefore, rather than adopting a strict, positivist approach which attempts to either validate or falsify ST:REAM, the assessment below attempts to:

i. gauge how well the model represents observations made of the reach-scale sediment status and,
ii. identify areas of potential improvement for the model and features of theoretical significance based on how and where the model outputs deviate from observations.

It is envisioned, therefore, that this assessment processes will emphasise the heuristic, as well as the predictive, value of ST:REAM as a modelling tool (Clifford *et al.*, 2005).

The remainder of this chapter first introduces two British river catchments that will be used as test cases: the River Taff in South Wales; and the Afon Einon in mid-Wales. These catchments are described in terms of their general environment and physiography, as well as the coarse sediment status of reaches observed through field and desk-based reconnaissance of their drainage networks. ST:REAM is applied to each of these catchments and the outputs are compared against the observed coarse sediment statuses. Both catchments are also used to explore the impacts that utilising variable bed surface material sizes and selecting alternative reach-scales have on the outputs from ST:REAM.

7.3 Description of test catchments

The two catchments used to develop and assess ST:REAM were selected primarily on the availability of data describing parameters of interest within the catchment. The justification for this is that river catchments with the maximum extent of data coverage possible enable a broader range of testing – models can be assessed using both the fullest data coverage possible and the typical data coverage within the same physical system.

The River Taff in South Wales has a high and consistent concentration of RHS sites relative to British river catchments in general (Figure 3.8B). At the outset of this study the RHS had been identified as a potentially useful data source for parameterising catchment-scale models of sediment dynamics, although subsequent examination in Chapter Three demonstrated otherwise. Further, the Environment Agency provided this study with LiDAR data covering the entire River Taff. The provision of this broad an extent of LiDAR data is relatively rare for academic studies and therefore the River Taff made an ideal test catchment for ST:REAM.

The Afon Einon in mid-Wales was the subject of a FRMRC funded Ph.D. examining the response of catchment sediment dynamics to agricultural land-use change (Henshaw, 2009). As part of the Ph.D. research, the morphology, sedimentology, hydrology and sediment dynamics of the Afon Einon catchment were studied over a 4-year period. As a result of the collaborative research scheme within the FRMRC, both the data gathered and the expert judgement of the researcher were made available to this study, making the Afon Einon an ideal test catchment.

A secondary justification for selecting the River Taff and the Afon Einon is that, whilst they cannot be representative of all British river catchments, they are not atypical of British rivers in general. They are exemplars of a common type of British river – steep, gravel-bedded rivers punctuated by bedrock. Understanding sediment dynamics within this type of river is particularly important due to their relatively dynamic nature resulting from their high stream powers.

7.3.1 River Taff catchment, South Wales

The main stem of the River Taff rises in the Brecon Beacons south-west of Pen-Y-Fan as the Taf Fawr (Big Taff) and flows more than 60km south to enter the Severn Estuary at Cardiff (Figure 7.4). Several major tributaries join the river along its course through the South Wales coal field. In downstream order, these are the: Taff Fechan (Little Taff), Taff Bargoed, Cynon, Nant Glydach, and Rhondda (Figure 7.4). The Taff system drains a catchment of approximately 500km^2. Annual rainfall ranges from 2400mm in the headwaters in the Brecon Beacons to 950mm at Cardiff. The Taff is characteristic of steep Welsh rivers, dropping an average of 11m per kilometre, from ~600m AOD at its source to ~0m AOD where it joins the Severn Estuary. Channels throughout the catchment are dominantly cobble-bedded, although reported bed surface materials range in size from coarse gravels to boulders.

Historically, the Taff was one of the most polluted rivers in Wales due to contamination by the coal mining industry, but it in the post-industrial era it now has a thriving population of salmonids (EA, 2009). Much work has already been carried out to improve water quality and passage for migratory fish. This has benefited both wildlife and the Welsh economy. The River Taff at Merthyr Tydfil has undergone a transformation over the last twenty years and was recently chosen as the location for the Rivers International Fly Fishing Championship (EA, 2009).

To assess the outputs of ST:REAM when applied to the Taff catchment, an attempt was made to identify the current coarse sediment status of channels distributed throughout the drainage network. This was achieved using a combination of field- and desk-based stream reconnaissance. The field-based element of the reconnaissance involved two fluvial geomorphologists (the author and Professor Clifford) making observations of the channel's morphological status along five of the seven network branches in the catchment.

Observations made of the channel's morphological status were guided by a standardised fluvial geomorphological reconnaissance procedure. Stream reconnaissance sheets are commonly used to record observations and measurements of the physical form of the channel, its riparian corridor, and (occasionally) its floodplain. A wide range of *pro-forma* stream reconnaissance sheets have been developed by different parties for slightly differing purposes. The format of some sheets places particular emphasis on the physical biotopes and functional habitats or a river, whilst others focus on the condition of the banks, or the risks posed by channel instability at bridges and other in-stream structures. None of the pre-existing sheets were explicitly applied here, but instead a list of indicators of channel stability status were used to identify the morphological status of the channel at observed locations. This list was taken from the Guidebook of Applied Fluvial Geomorphology (Thorne *et al.*, 2010) and is reproduced in Table 7.1. However, despite attempting to standardise judgements of channel morphological status using indicators from this list, it is recognised that any assessment of channel condition is influenced by its state relative to the rest of the catchment. This is the case because the observed erosional, stable or depositional status of a reach is generally perceived in relative, rather than absolute, terms. Reaches that cannot be differentiated when considered in isolation may be designated differently dependent on the catchment context, in general, and comparisons to adjacent reaches, in particular. For example, a reach that appears marginally depositional in the context of an upland, headwater catchment dominated by erosion could be designated as slightly erosional if it were observed in the context of a lowland catchment dominated by depositional processes and forms.

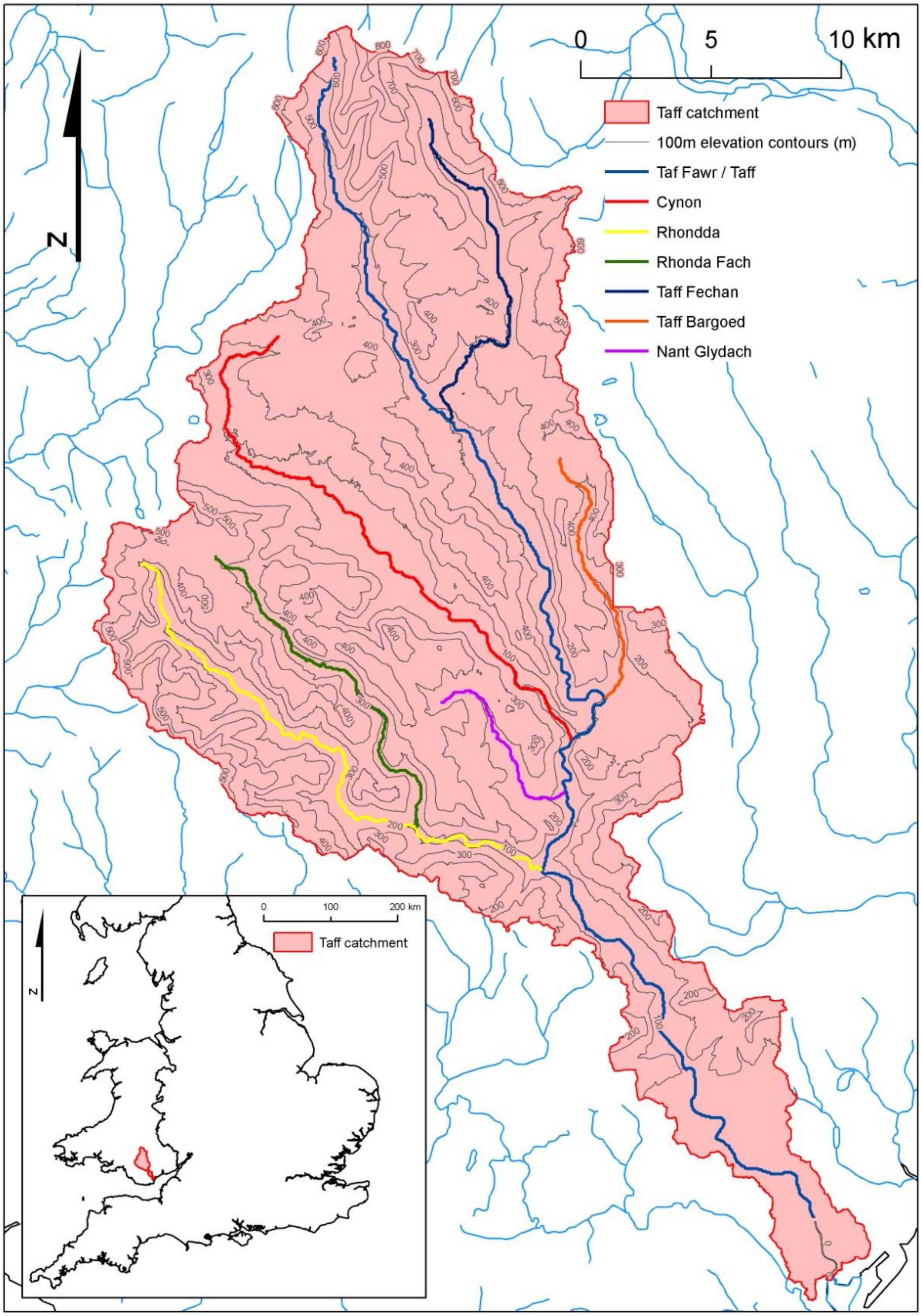


Figure 7.4 Location map of the River Taff catchment in South Wales

Selection of sites for detailed observation during the catchment reconnaissance, was based around the reaches identified and applied using the ST:REAM reach delineation process. Within the branches reconnoitred, at least one observation was made in each of the reaches identified by the functional reach boundary hunting algorithm (Figure 7.5). This sampling design clearly has implications regarding which aspects of the ST:REAM approach these observations can be used to assess. As the observations are spatially organised according to the model's reach boundaries, they are based on the assumption that those boundaries are appropriate. The limitation that this imposes upon a rigorous assessment of the entire ST:REAM approach must be appreciated when the findings are considered.

Field-based observations were supported by a desk-based study using Google aerial imagery (Google, 2009). This imagery was used to complete the channel reconnaissance by making observations of channel status in locations where field-based observations were not possible. The resultant 'observed' channel sediment status of reaches within the Taff catchment is displayed in Figure 7.6.

Table 7.1 Indicators of channel stability status. Taken from Thorne et al. (2010)

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

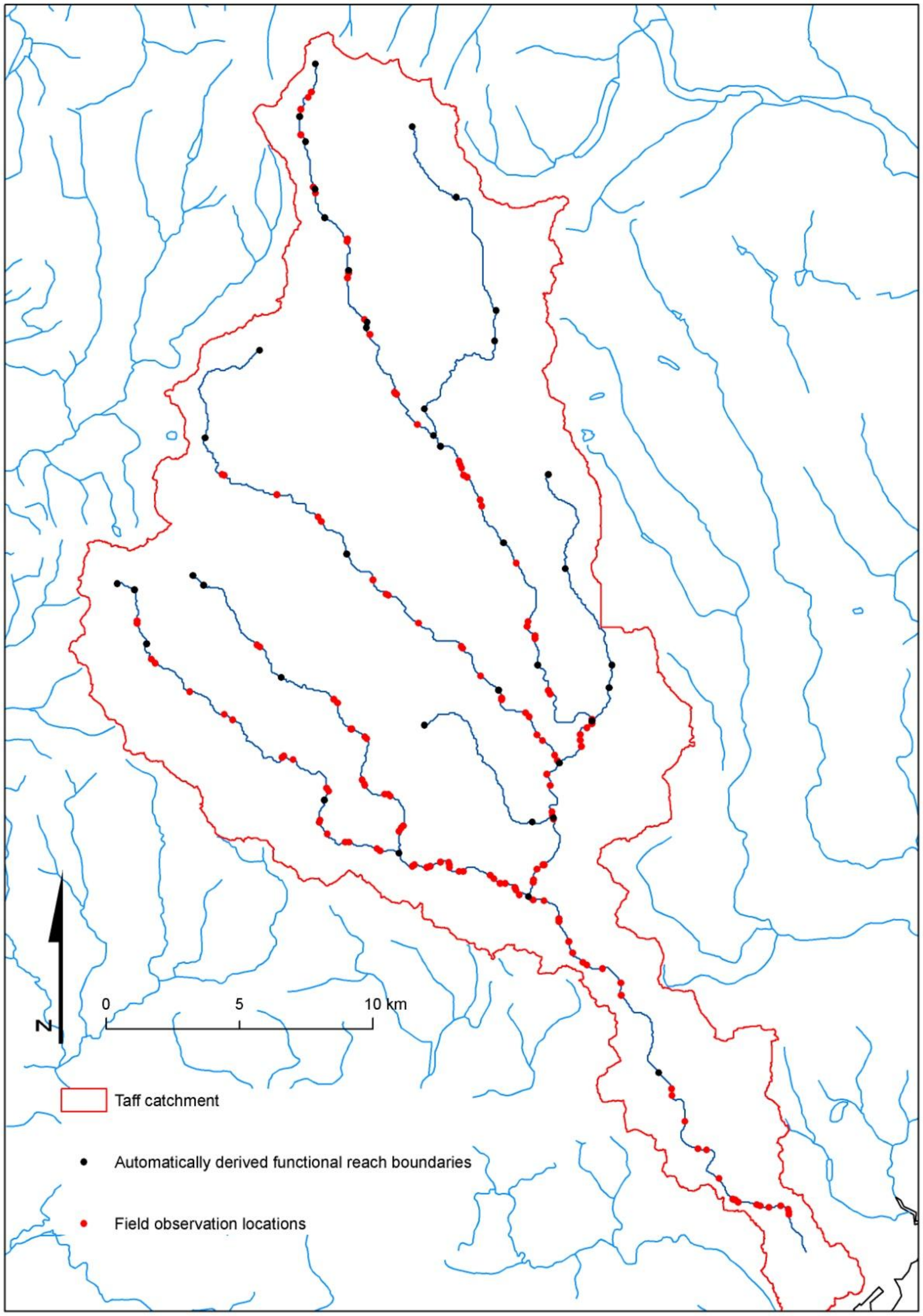


Figure 7.5 Location of field-based channel observations made throughout the River Taff catchment in relation to automatically identified functional reach boundaries.

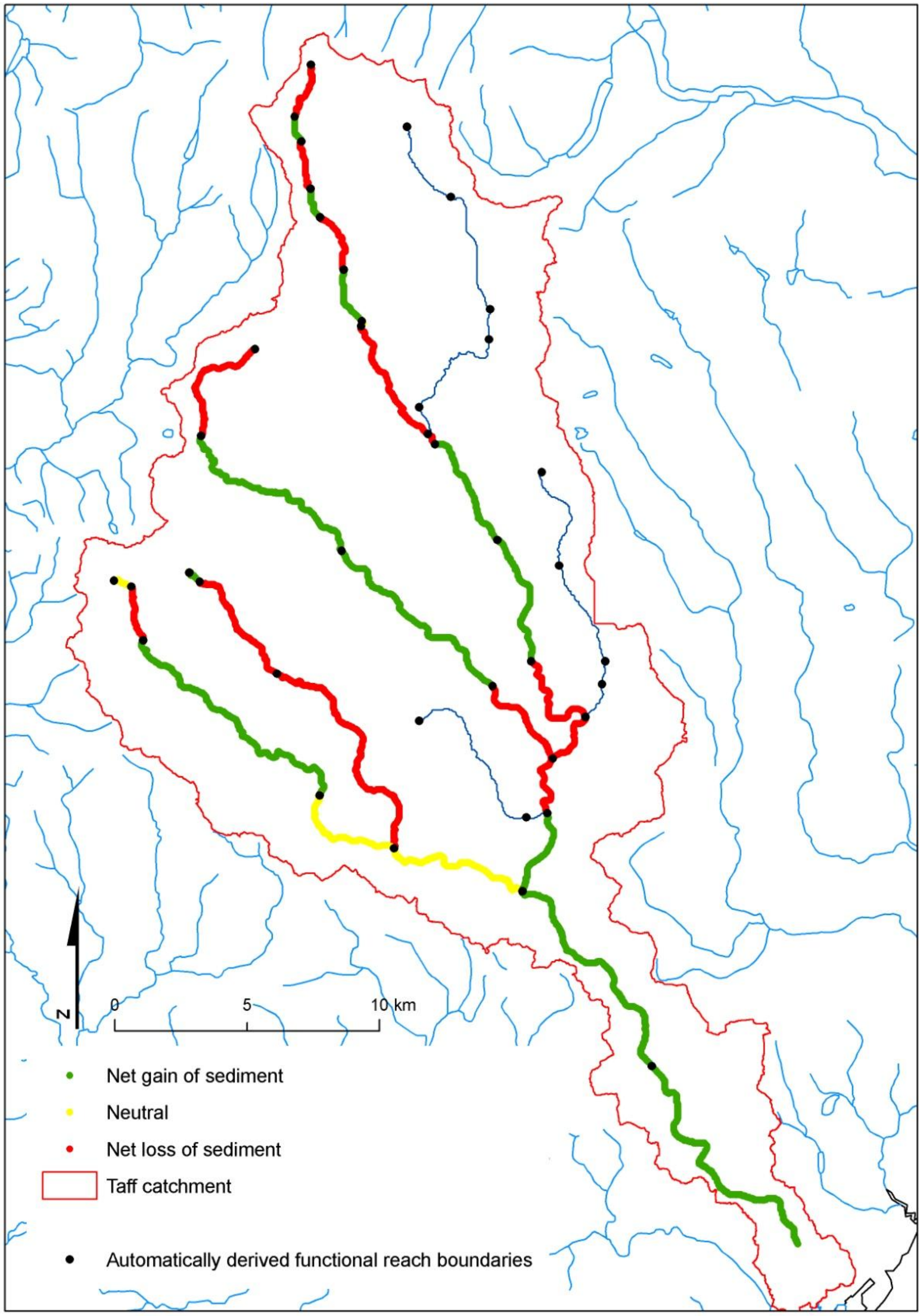


Figure 7.6 Observed channel sediment status for automatically identified functional reaches within the River Taff catchment based on field- and desk-based reconnaissance.

7.3.2 Afon Einon catchment, mid-Wales

The Afon Einion is a small, gravel-bed stream (total drainage area = 18 km^2) that converges with the Afon Banwy near the village of Llanfair Caereinon in Powys (Figure 7.7). It is dominated by three tributaries: the Nant Pen-y-cwm (which is treated here as the main stem); the Nant Gelli-Gethin; and the Nant Melin-y-grûg. The physiographic and climatic characteristics of the catchment are typical of mid-Wales (Henshaw, 2009). The catchment ranges in elevation from ~424m AOD near the source of the Nant Melin-y-grûg tributary to ~128m AOD at its confluence with the Afon Banwy, and is characterised topographically by gently undulating hills, with steeper slopes where rock outcrops are present. Average annual precipitation in the catchment is 1501mm with a mild, maritime climate (Henshaw, 2009).

Economic, political, social and environmental drivers have heavily influenced landuse and land management practices in the Afon Einon catchment over the last century (Henshaw, 2009). Agriculture shifted from small, mixed purpose farming to intensive livestock grazing following World War II in response to policies designed to increase British food production and fields expanded as hedgerows were removed during grassland improvement works. Local stocking levels and the average weight of individual sheep increased dramatically as a result of the grassland improvement. Importantly, these changes were not implemented uniformly throughout the Afon Einon catchment. Widespread grassland improvement was undertaken in areas drained by the Nant Pen-y-cwm (the main stem of the Afon Einon) and the Nant Gelli-Gethin tributary, but agricultural development was far more limited in the upper reaches of the Nant Melin-y-grûg tributary (Henshaw, 2009).

This contrast in land management practices between adjacent sub-catchments enabled the Afon Einon catchment to be used within a Flood Risk Management Research Consortium (FRMRC) project that aimed to identify the impact of agricultural land management on catchment hydrology (Lee *et al.*, 2006) and sediment dynamics (Henshaw, 2009). The in-depth knowledge of the sediment systems within the Afon Einon gained during this project (Alex Henshaw, University of Nottingham, personal communication, 2009) was used to define the ‘observed’ sediment status of channels in the catchment against which the outputs from ST:REAM were then assessed. Again, whilst a formal, standardised reconnaissance procedure was not used to make these observations, the observed sediment statuses of the channel were informed by the indicators described in Table 7.1.

Unlike the observations made of the River Taff catchment in Section 7.3.1, the reach boundaries for the Afon Einon catchment observations were defined independently from the modelling process and were instead based on Dr Henshaw’s detailed knowledge of sediment dynamics and morphological adjustments in the fluvial system, gained during 3-years of doctoral research centred on this small catchment (Alex Henshaw, University of Nottingham, personal communication, 2009). However, the boundaries are still based on the identification of internally homogenous and comparatively distinct ‘functional’ reaches within the channel network. The key difference is that for the Afon Einon, these functional boundaries have been identified based on independent observations of the catchment; whilst for the River Taff the functional boundaries were automatically identified using ST:REAM’s boundary hunting algorithm. The resultant ‘observed’ sediment status of reaches within the Afon Einon catchment is displayed in Figure 7.8.

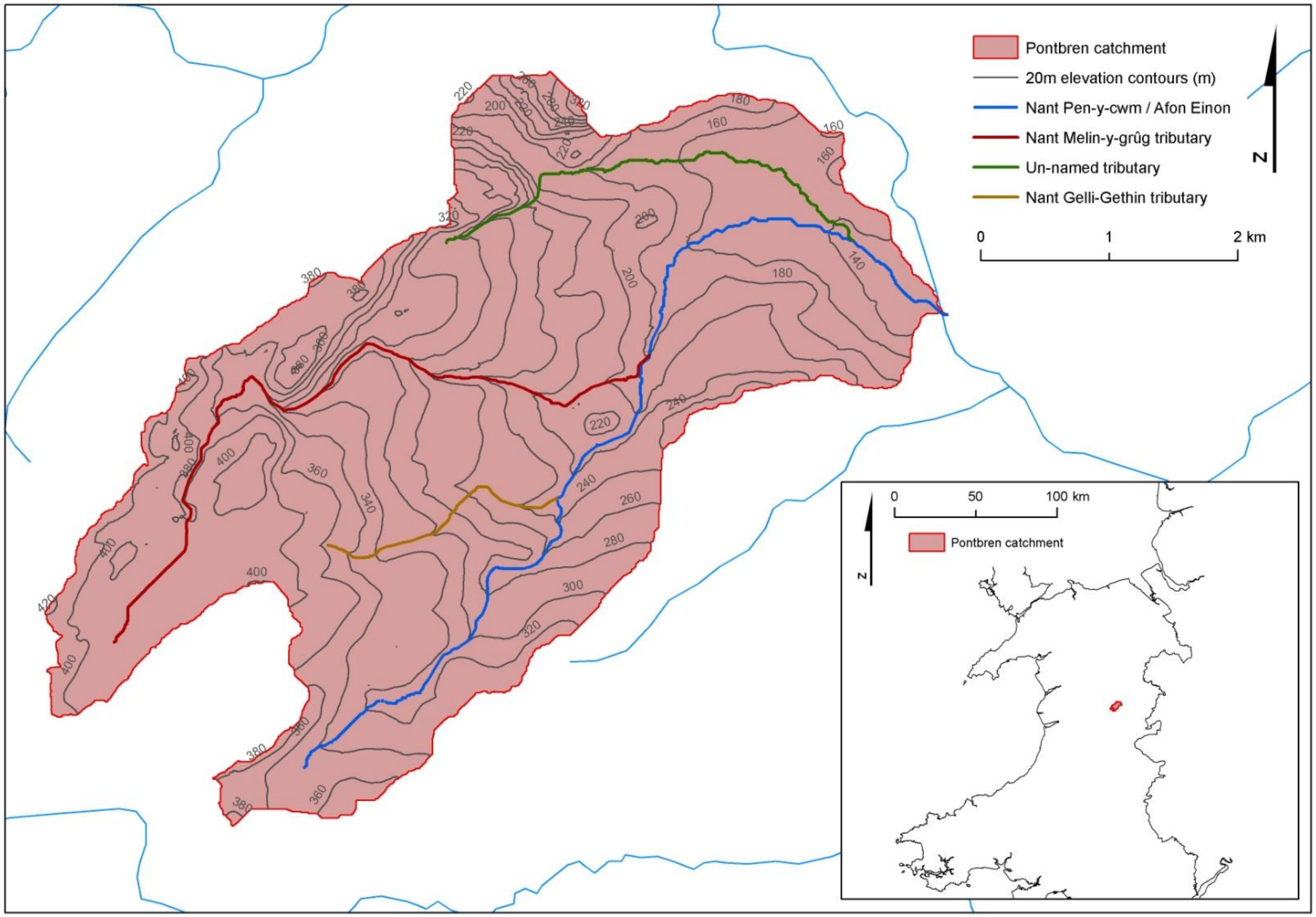


Figure 7.7 Location map of the Afon Einon catchment in mid-Wales.

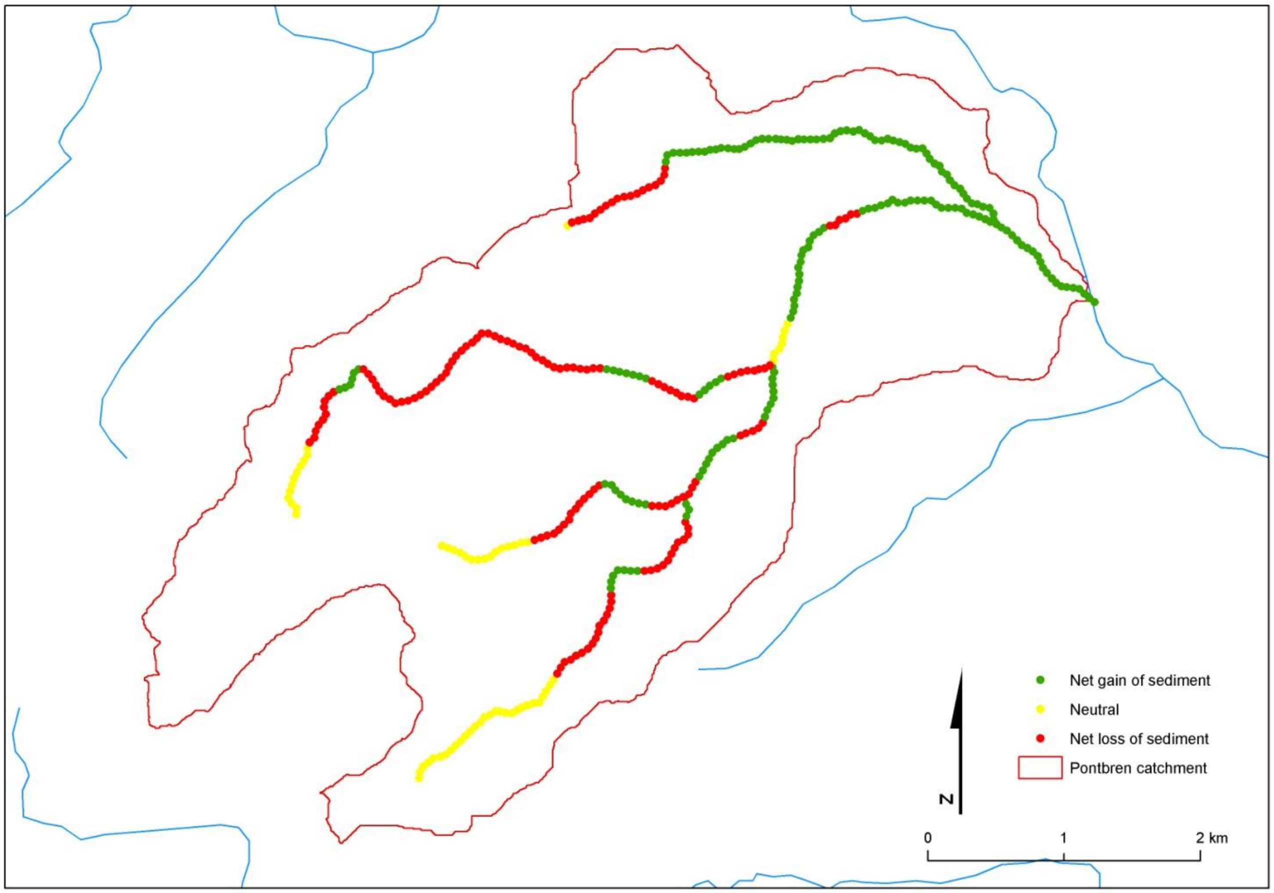


Figure 7.8 Observed channel sediment status for observationally identified functional reaches within the Afon Einon catchment based on expert knowledge of the system.

7.4 Model assessment

7.4.1 Model assessment against observations for test catchments

Figure 7.9 provides an illustration of outputs from ST:REAM based on application to the Taff catchment assuming a uniform bed surface material size of 0.1m (cobble), with functional reach boundaries that explain 1% of the total variation in predicted Q_{MAF} bed surface material transport capacity. It should be noted that the most upstream reach in each branch cannot be assigned a capacity supply ratio because it has no upstream neighbour from which to provide the 'supply'. Comparison with the observed reach sediment statuses displayed in Figure 7.6 reveals many similarities. For example, towards the upper reaches of the Taff main stem, ST:REAM identifies three reaches with CSRs (capacity supply ratios) of less than 0.1 separated by reaches with CSRs greater than 10 (points A1, A2 and A3 on Figure 7.9). Based on the catchment reconnaissance, these were found to correspond to three large reservoirs (e.g. Figure 7.10A) and the severely sediment-starved reaches between them (e.g. Figure 7.10B), respectively. Other examples of reaches where the CSR predicted by ST:REAM correlates closely with the observed sediment status include the two, long adjacent reaches on the River Cynon tributary branch (Figure 7.4) with predicted CSRs of less than 0.1 (points B1, and B2 on Figure 7.9), followed by a reach just upstream of the confluence with the Taff main stem, with a modelled CSR greater than 10 (point C on Figure 7.9). In the field, these reaches were found to correspond to two predominantly depositional reaches (e.g. Figure 7.10C and Figure 7.10D), followed by a predominantly erosional reach (e.g. Figure 7.10E). A final example of reaches where the outputs from ST:REAM are consistent with the field observations is the lower stretch of the Taff, downstream of its confluence with the Rhonnda tributary (Figure 7.4). Here, the observed status of both reaches in this stretch of river was depositional (e.g. Figure 7.10F), which supports the modelled CSRs of below unity (points D1 and D2 on Figure 7.9).

However, despite the good overall association between the observed status of the reaches and the modelled CSRs, some reaches are obviously dissimilar. For example, just after the third reservoir on the main stem of the Taff, there is a very short reach with a modelled CSR greater than 10 (point E on Figure 7.9), that is followed by a long reach with a modelled CSR less than 0.1 (point F on Figure 7.9). However, in the field, this second reach was observed to be predominantly erosional (e.g. Figure 7.10G and Figure 7.10H). The cause of this misrepresentation was identified as originating from conditions in a short reach directly downstream of the reservoir. This reach has an extremely high transport capacity and so was modelled as delivering an extremely high supply to its downstream neighbour. As a result, its downstream neighbour was predicted to have a CSR less than 0.1. Actually, the short reach directly downstream of the reservoir is the concrete-lined tail race for reservoir outflow (Figure 7.10I), which clearly does not produce the high sediment output predicted by ST:REAM due to its non-erodible channel boundaries. Consequently, the supply to its downstream neighbour is considerably lower than was modelled by ST:REAM, explaining the misrepresentation of the downstream CSR.

A similar situation was identified approximately halfway along the main stem of the Taff, in the reach just downstream of the confluence with the Bargoed Taf tributary (Figure 7.4). Here, ST:REAM predicted a CSR of less than 0.1 (point G on Figure 7.9), yet observations of the channel suggest that the reach is predominantly erosional (e.g. Figure 7.10J). In this case, the cause of the misrepresentation of reach CSR was identified as being conditions in the final reach of the Bargoed Taf tributary (point H on Figure 7.9). This has an extremely high transport capacity, so that ST:REAM predicted an extremely high sediment supply to the main stem reach immediately downstream of the confluence. As in the example above, while the final reach of the Bargoed Taf tributary has a high *potential* to transport coarse sediment, it is unable to satisfy its capacity, because it is confined within a concrete channel downstream of a reservoir (Figure 7.10K).

In light of these findings, the ST:REAM model for the Taff catchment was modified so that all reaches identified in the field and desk-surveys as having completely non-erodible boundaries (i.e. concrete-lined channels) were represented as such within the model. This was achieved by limiting the maximum output of such a reach to the input that it receives from its upstream neighbours.

Revised outputs from this modified model of the Taff catchment are displayed in Figure 7.11. The CSRs predicted by ST:REAM when the non-erodible reaches are accounted for (Figure 7.11) more closely represent the observed sediment status of the reaches (Figure 7.6) than the CSRs when the concreted reaches are unaccounted for (Figure 7.9). It should be noted that the most upstream reach of the Rhondda branch (point A on Figure 7.11) has been identified as having a non-erodible boundary and therefore no supply was predicted for the second most upstream reach of that branch (point B on Figure 7.11). As a result, the second most upstream reach of the Rhondda branch was not allocated a capacity supply ratio.

Figure 7.12 provides an illustration of outputs from application of ST:REAM to the Afon Einon catchment assuming a consistent bed surface material size of 0.1m (cobble), with functional reach boundaries explaining 1% of the total variation in predicted Q_{MAF} bed surface material transport capacity. The smaller size of this catchment reduces the number of reaches identified by ST:REAM at the 1% zonation level compared to the Taff catchment. In fact, the Nant Gelli-Gethin and Nant Melin-y-grûg tributaries (Figure 7.7) have both been designated as single reaches (points A and B on Figure 7.12 respectively). As identified earlier, unlike the observed reach statuses for the Taff catchment, the observed status of reaches within the Afon Einon catchment in Figure 7.8 were not constrained by the reach boundaries identified by ST:REAM. Therefore, it is more difficult to make direct comparisons between the observed and modelled reach status. Nevertheless, all of the reach CSRs predicted by ST:REAM in Figure 7.12 seem appropriate when compared to the channel statuses designated in Figure 7.8. Further, research experience with this river system confirms that, at a broad-scale (R = 0.01), the Afon Einon could indeed be divided into three reaches with the sediment statuses as predicted by ST:REAM in Figure 7.12 (Alex Henshaw, University of Nottingham, personal communication, 2009).

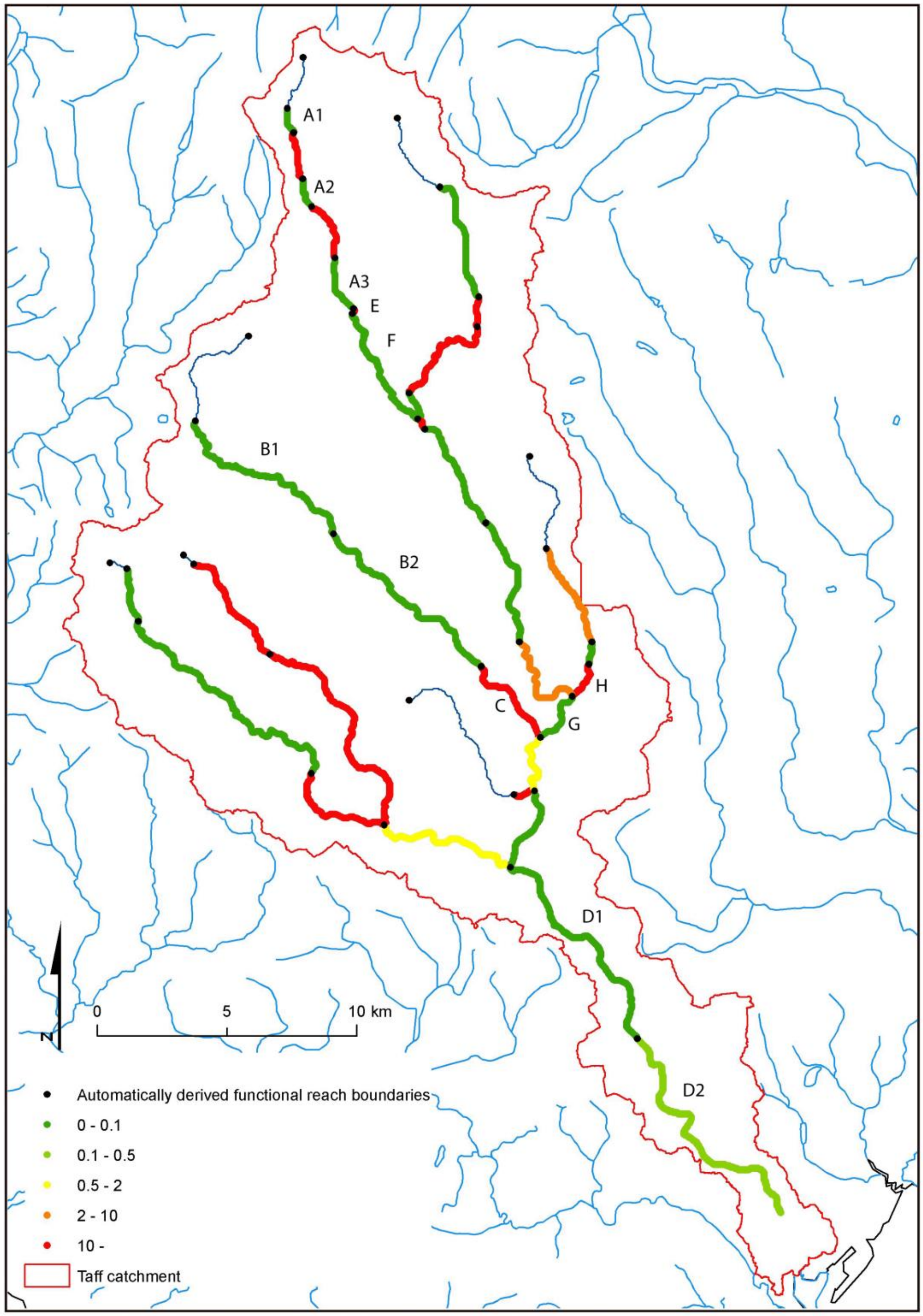


Figure 7.9 ST:REAM predicted capacity supply ratios for the River Taff catchment, South Wales. All cobble bed surface material, 1% zonation reach boundaries.

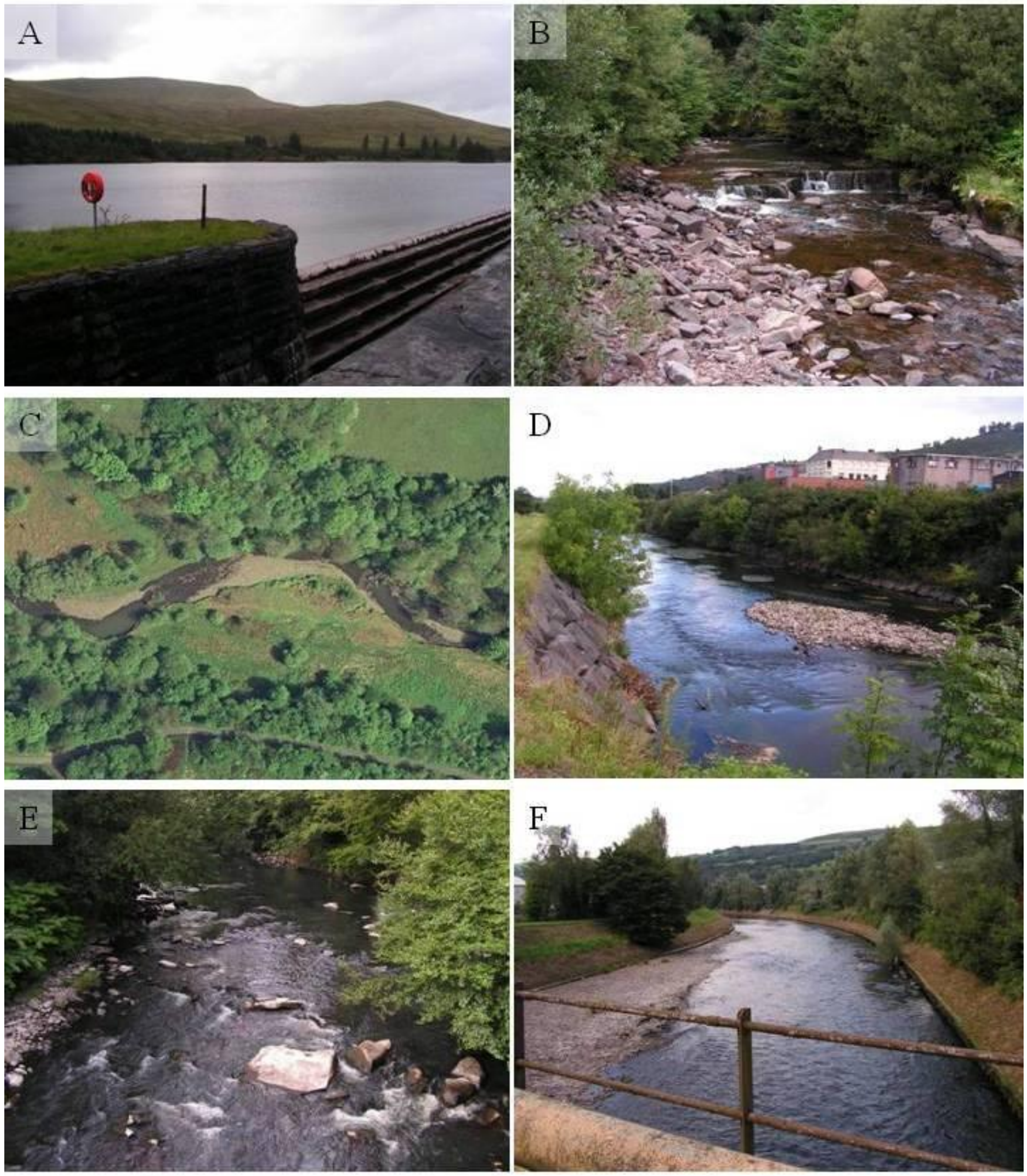


Figure 7.10 Observations of channel sediment status within the River Taff catchment, South Wales. (A) Brecon Reservoir, River Taff main stem; (B) Predominantly erosional reach downstream of the Brecon Reservoir, River Taff main stem; (C) Predominantly depositional reach on the River Cynon, taken from Google (Google, 2009); (D) Predominantly depositional reach on the River Cynon; (E) Predominantly erosional reach on the River Cynon, just before the confluence with the River Taff; (F) Predominantly depositional reach on a downstream reach of the River Taff.

Figure 7.10 Observations of channel sediment status within the River Taff catchment, South Wales. (G) Predominantly erosional reach on the River Taff, downstream of the Llwynon Reservoir; (H) Predominantly erosional reach on the River Taff, downstream of the Llwynon Reservoir, taken from Google (Google, 2009); (I) Steep concreted run-off from the Llwynon Reservoir on the River Taff; (J) Predominantly erosional reach on the River Taff, downstream of the confluence with the Bargoed Taf; (K) Steep concreted run-off from the Reservoir on the Bargoed Taf, just upstream of the confluence with the River Taff, taken from Google (Google, 2009).

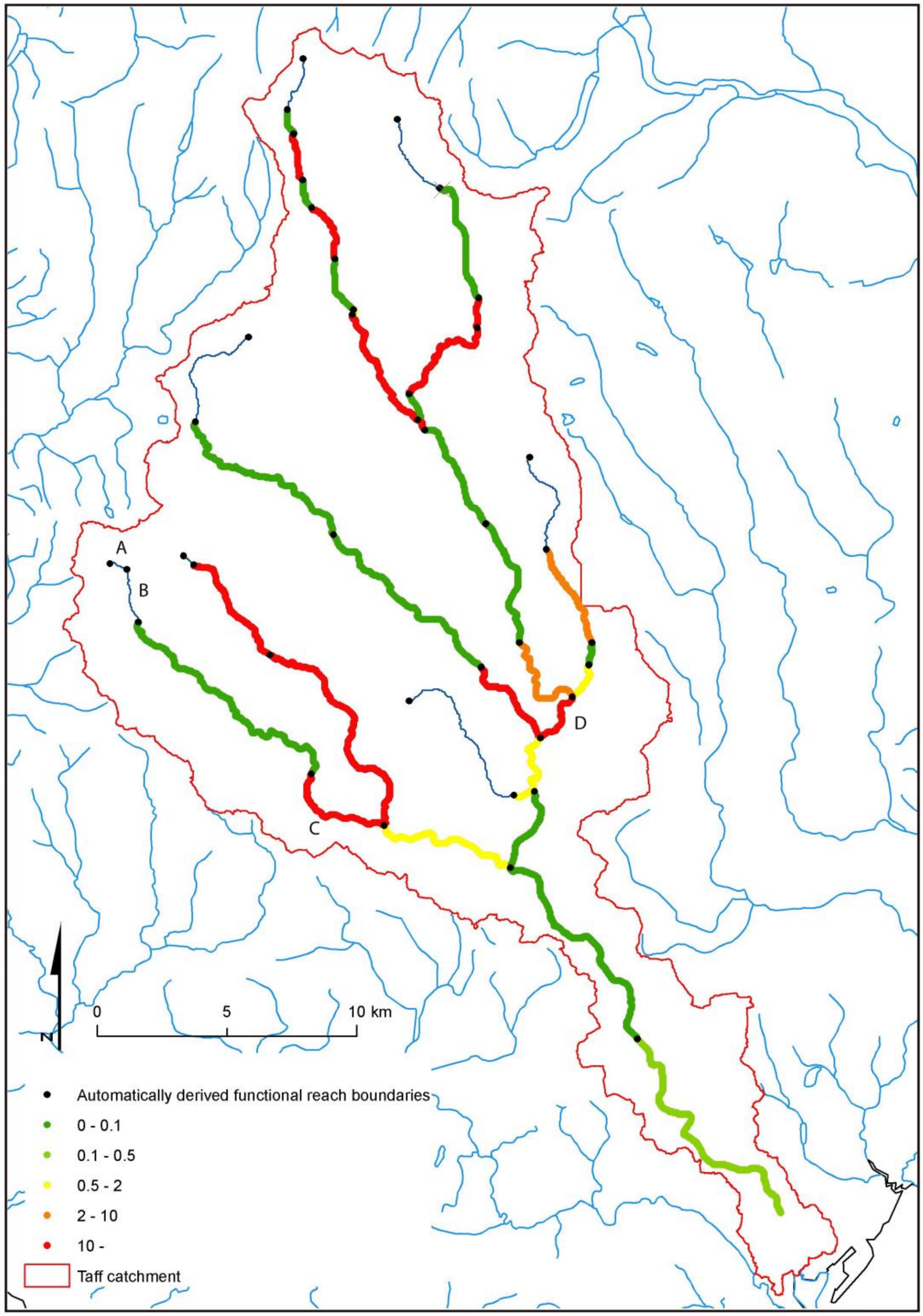


Figure 7.11 ST:REAM predicted capacity supply ratios for the River Taff catchment, South Wales. Cobble bed surface material with supply-limited concreted sections, 1% zonation reach boundaries.

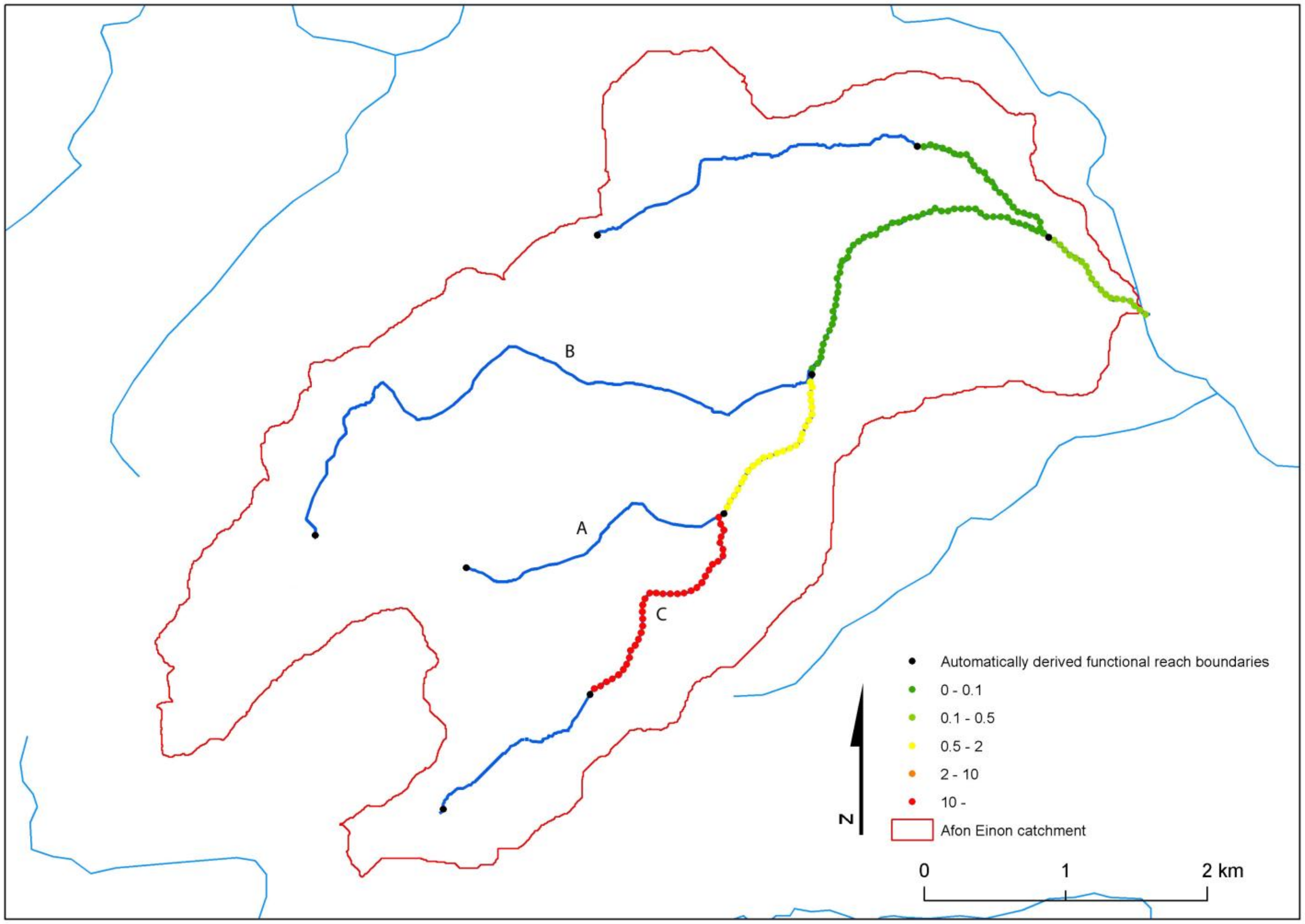


Figure 7.12 ST:REAM predicted capacity supply ratios for the Afon Einon catchment, mid-Wales. All cobble bed surface material, 1% zonation reach boundaries.

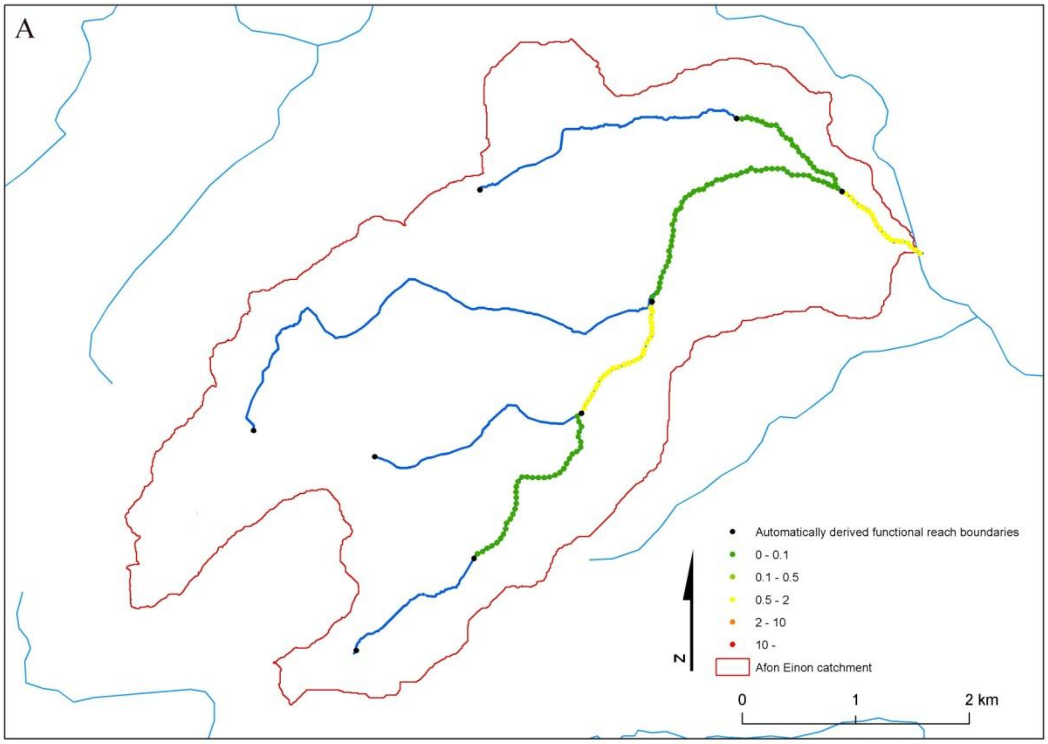
7.4.2 Assessing the influence of bed surface material variability on ST:REAM outputs

Section 4.5 suggested that, if bed material size is considered as a dependent, rather than an independent factor within catchment-scale sediment dynamics, then it is unnecessary to input detailed information on bed material sediment size when running the ST:REAM model. In fact, relatively good coverage of bed material data are available for both test catchments. The Taff catchment has a relatively dense coverage of RHS sites (Figure 3.8B), each with a record of the dominant bed material type present at the ten spot checks; and the main stem of the Afon Einon has undergone an intensive bed material measurement survey, including ~50 Wolman pebble counts over ~8km (Henshaw, 2009). The relatively dense coverage of bed material size data makes it possible to identify the impact of assumed bed material size uniformity on the outputs from ST:REAM in both catchments.

Two different means of accounting for variations in bed material size within a reach-based sediment balance model were introduced in Section 4.5. The first (static) approach involves treating each reach in isolation in terms of its sediment type so that the capacity of a reach to transport its own bed material size is compared against the supply of material from upstream reaches which are transporting their own bed material size. This is similar to the approach adopted in the REAS method (see Section 3.3.5), where a reach energy budget is calculated by comparing the Annual Geomorphic Energy (AGE) for a reach (using its own bed material to define the critical power for entrainment) against the AGE value for its upstream neighbour (using the upstream neighbour’s own bed material to define its critical power).

The second (dynamic) means of accounting for variations in bed material size within a reach-based sediment balance model is to allow sediment fractions to pass through the catchment network preferentially based on their size. This means that a reach can transport a sediment fraction from an upstream reach if it is easier to transport (smaller) than the material on its bed. As a result, the sediment balance for a reach is calculated based on the combined mass of all fractions entering the reach compared with the combined mass of all fractions leaving the reach. This type of treatment of bed material variation is similar to that applied by SIAM (see Section 3.3.5).

Alternative versions of ST:REAM were thus developed, each applying one of these approaches to accounting for changes in bed material size between reaches. They are defined as Version A (where bed material sizes are isolated within their original reaches - static), and Version B (when bed material sizes can be routed through the catchment network - dynamic). They were each applied to both the Afon Einon catchment, with the bed material sizes for each reach based upon measured data, and the River Taff catchment, with bed material sizes for each reach inferred from RHS classifications. The outputs of these bed material sensitive applications of ST:REAM for the Afon Einon and River Taff catchments are displayed in Figure 7.13 and Figure 7.14, respectively.



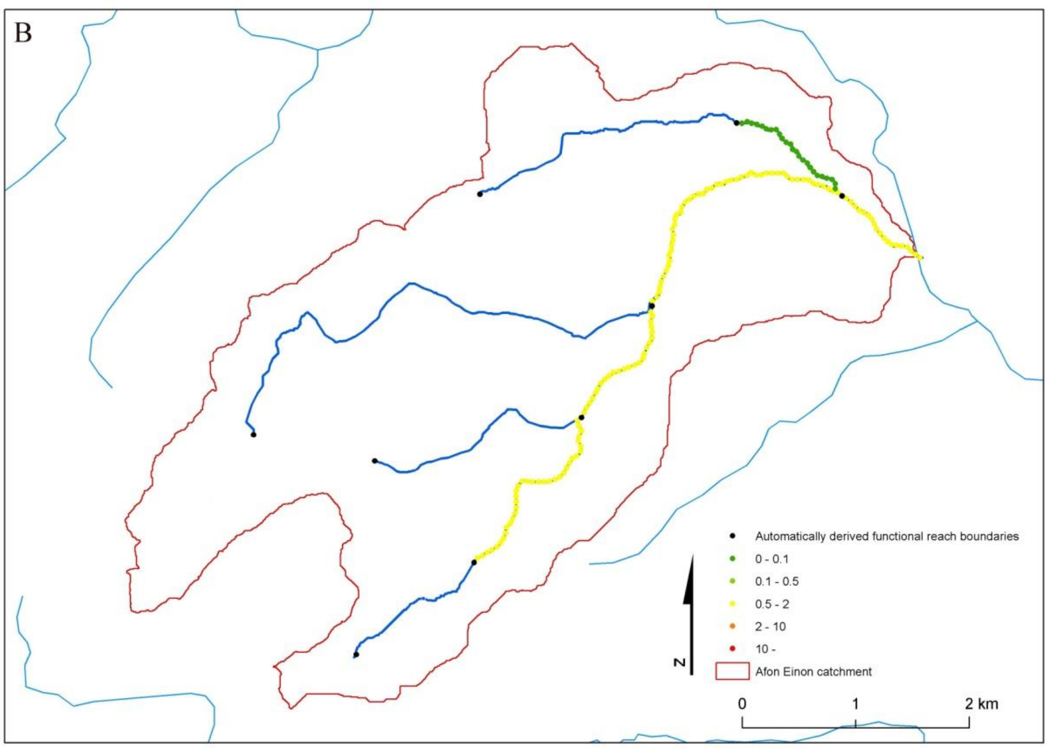


Figure 7.13 ST:REAM predicted capacity supply ratios for the Afon Einon catchment, mid-Wales using measured bed material sizes. 1% zonation reach boundaries. (A) Static - No routing of sediment fraction. (B) Dynamic - Routing of sediment fractions.

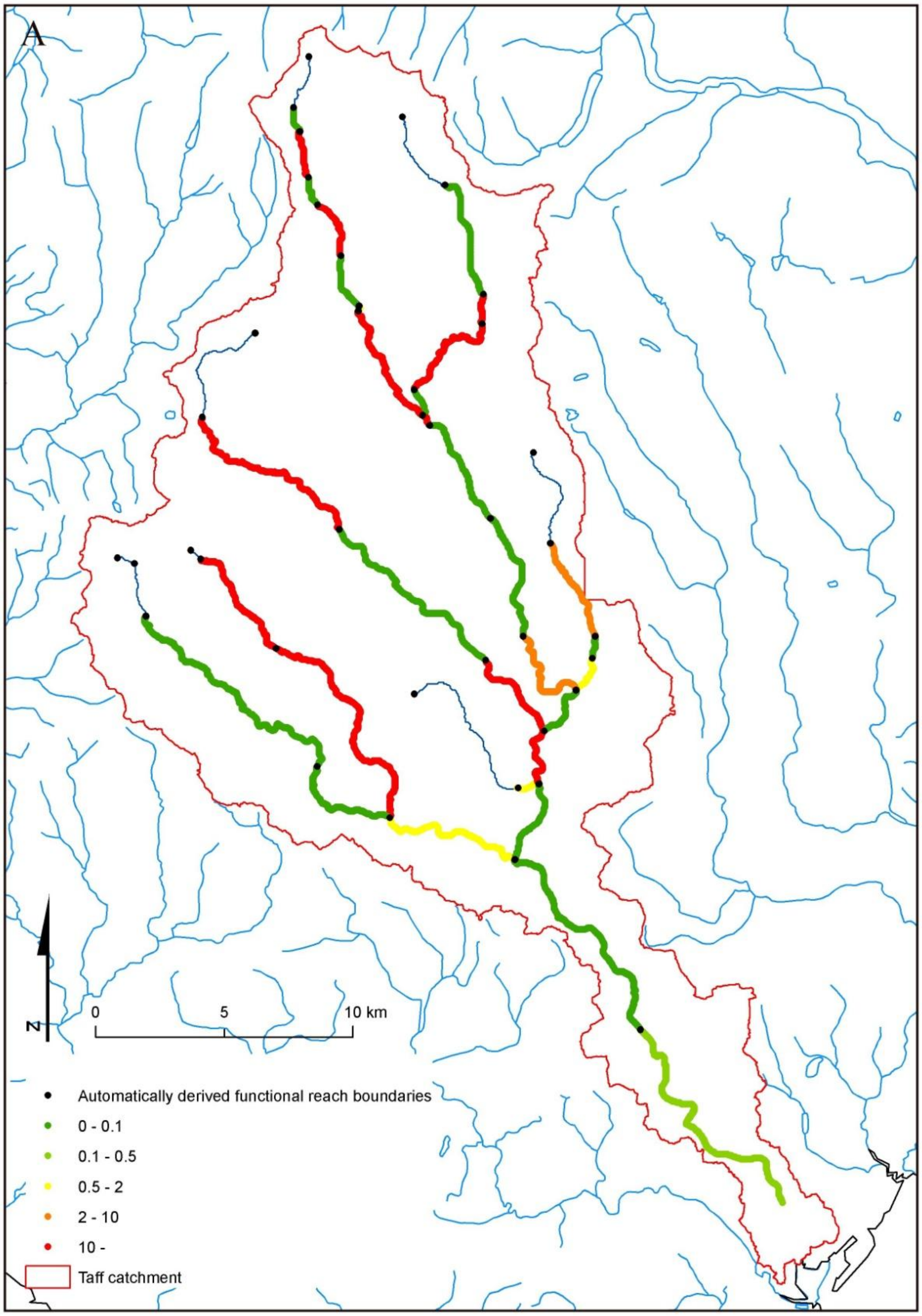


Figure 7.14 ST:REAM predicted capacity supply ratios for the River Taff catchment, South Wales using RHS bed material sizes. 1% zonation reach boundaries. (A) Static - No routing of sediment fraction.

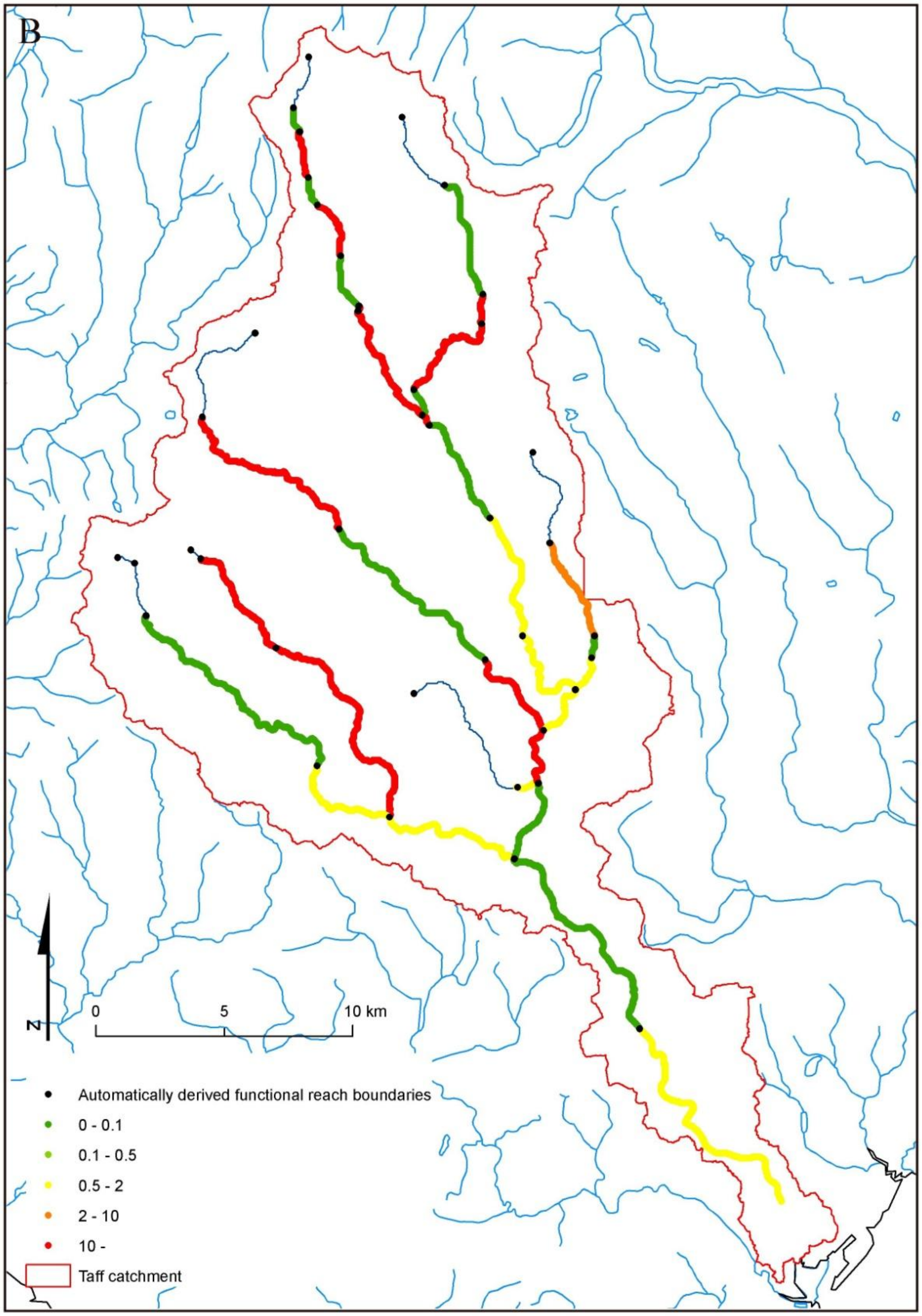


Figure 7.14 ST:REAM predicted capacity supply ratios for the River Taff catchment, South Wales using RHS bed material sizes. 1% zonation reach boundaries. (B) Dynamic - Routing of sediment fractions

In the case of the outputs for the Afon Einon catchment, the predicted reach CSRs displayed in Figure 7.13B differ both from those based on the uniform sediment assumption in Figure 7.12 and from each other. Exploring the causes of these differences helps to understand the influence of the different means of accounting for bed material sizes within ST:REAM. For example, the second reach on the main stem of the Afon Einon is predicted as having a CSR of greater than 10 in the original model (point C on Figure 7.12), whilst version A of the model (comparing the capacity of reaches to transport just their own bed material) predicts a CSR less than 0.1 (Figure 7.13A). The reason for this is that, whilst the stream power of the second reach on the main stem is greater than its upstream neighbour, its measured bed material is much larger (D_{50} of 0.05m versus 0.0024m). Therefore, according to Version A (static), the higher energy second reach on the main stem can transport far less of its own coarser bed material than the quantity of the finer material that the lower energy upstream neighbour can transport and supply to it. When the same reach is considered using the outputs of Version B (dynamic), the predicted CSR is found to be approximately 1 (Figure 7.13B). This is because, despite the reach in question having more stream power than its upstream neighbour, the total mass of the larger sediment fraction that it can then entrain from its own bed is insignificant. The reach is balanced because the mass of fine sediment transported into the reach from upstream can be transferred downstream without net deposition. In fact, in Figure 7.13B, the dominating impact of the large mass of fine sediment entrained from the first reach can be seen to influence not just the adjacent reach, but all of the reaches downstream.

Similar effects are apparent in the outputs for the Taff catchment displayed in Figure 7.14A and Figure 7.14B. On initial examination, Figure 7.14A appears similar to the original ST:REAM outputs in Figure 7.11. However, this is largely due to the fact that the majority of RHS sites within the Taff catchment have cobble as their modal bed material type, and cobble is the bed material applied uniformly in the model used to produce Figure 7.11. Closer examination of the differences between Figure 7.11 and Figure 7.14A reveals issues similar to those identified in the Afon Einon when using the static approach to representing bed material variability. For example, the reach on the Rhondda that is just upstream of the confluence with the Rhondda Fach has a CSR of less than 0.1 according to Version A, while it has a CSR greater than 10 in the original version of ST:REAM (point C on Figure 7.11). The reason for this is that this reach is defined by RHS indicators as having a boulder-bed so that, even though it has greater stream power than its upstream neighbour, based on its larger sediment size its transport capacity is far smaller than its incoming supply. A similar effect is produced on the reach on the main stem of the Taff just downstream of the confluence with the Bargoed Taf, which is identified in the RHS as having a boulder-bed, while its upstream neighbour is defined as having a cobble-bed (point D on Figure 7.11). Therefore, despite the reach in question having greater stream power, it is modelled as being able to transport less of its boulder bed material than the upstream reach supplies through transport of sediment derived from its cobble bed.

Figure 7.14B also appears to be largely similar to the original ST:REAM outputs in Figure 7.11. However, the differences present reinforce the effects observed when Version B was applied to the Afon Einon. For example, the reach on the main stem just downstream from the confluence with the Bargoed Taf is defined as having a near neutral CSR in Figure 7.14B when it was previously correctly defined as highly erosional (point D on Figure 7.11). The reason for this is that, as identified above, it is defined by RHS as having a boulder-bed. Therefore, although it has far more stream power than its upstream neighbour and so can easily transport the material supplied to it from upstream, because its own boulder bed material is so difficult to entrain, it can only transport a small quantity of it. Consequently, its outgoing sediment load is modelled as being only slightly greater than its incoming load.

This section has explored how introducing two different means of representing bed material variability would impact the outputs of ST:REAM. It is evident from comparing the outputs against the observed sediment status within the catchment, and the original outputs from ST:REAM, that incorporating measured variability in bed material actually reduces the model's accuracy. Two major factors contribute to this: the suitability of the bed material data sources used; and the appropriateness of using bed material size as an independent variable within catchment-scale analysis of sediment dynamics.

Despite their relatively good coverage, neither of the two bed material data sources provides a complete representation of bed material variability within the study catchments. In particular, the RHS data used within the River Taff catchment is not ideal in terms of either the accuracy of its bed material classifications (Figure 3.19), or the precision of its classes. Even if the size classifications in an RHS record were 100% accurate, adjacent reaches with only slightly different bed materials can be allotted classes that are extremely different in their potential mobility. For example, in the analysis above, the reach on the Rhonnda that is just upstream of the confluence with the Rhonnda Fach was identified as being defined as being boulder-bedded in the RHS database, while its upstream neighbour was defined as being cobble-bedded. In reality, bed material sizes in these reaches are far more similar than their RHS classifications suggest, exaggerating differences in bed mobility and generating inaccurate predictions of CSR.

Even though the bed material data available for the Afon Einon catchment is more accurate and precise than RHS data, it still does not provide an ideal representation of bed material variability within the catchment. Bed material measurement is widely recognised as being strongly dependent on the location of the sample within the channel (Gomez, 1991). Further, measurement of bed material sizes at discrete channel cross-sections within a catchment cannot fully represent the natural variability within a catchment.

However, even if the poor performance of the versions of ST:REAM that incorporate bed material variability is attributed to the unsuitability of the bed material data used, the data used within these case studies represents the best that is available across British catchments. RHS coverage for the Taff catchment is amongst the highest nationally, and measured river bed material size data, like that for the Afon Einon, is extremely rare. Therefore, with respect to the original aims of this thesis, it is not realistically possible to improve bed material representation beyond what has been applied here.

It was argued in Section 4.5 that, within a uni-directional steady-state treatment of coarse sediment dynamics, the bed material size observed within a reach can be considered less of a driving influence in catchment sediment dynamics, and more a response variable indicative of the sediment status of the reach in question. The results produced within this section support this proposal. Where a reach has a relatively high stream power, it is likely to have a relatively coarse bed material (the boulder-bedded reach downstream of the confluence with the Bargoed Taf, for example). When bed material sizes are modelled as consistent throughout the catchment, this type of reach is generally predicted as having a high CSR. However, when bed material sizes are modelled as observed, differences in bed material size can disguise or even overwhelm the differences in stream power so that this type of reach is predicted as having a neutral or even low CSR. Based on the model assessment reported in this section it is therefore concluded that bed material size is indeed best modelled as uniform within ST:REAM. However, whilst bed material size is best modelled as uniform within an approach like ST:REAM as it deals with sediment balances rather than actual sediment fluxes, where users wish to predict sediment fluxes it *is* necessary to account for bed material sizes, as is done so in sediment routing models.

7.4.3 Assessing the influence of reach scale on ST:REAM outputs

Section 7.4.1 above demonstrated that, provided completely unerodible, concreted reaches are accounted for, ST:REAM can produce CSR outputs that represent the general trends in morphological status observed in the field. However, the scale at which these trends are represented is highly dependent on the length of the reaches used within the model, and this focuses attention on the level of explanation to which the zonation algorithm is extended. When the model was applied to the Afon Einon catchment (Figure 7.12), a 1% level of explanation identified only 4 reaches along the main stem. Because of the small size of the Afon Einon catchment, representation by just four reaches is not unreasonable and would probably be useful for most broad-scale, catchment management purposes. However, a river researcher interested in variations in morphological status at a finer scale would wish to generate more reaches, making it necessary to extend the model's automatic zonation procedure beyond 1% explanation of the total variation. Figure 7.15A and Figure 7.15B demonstrate the outputs from ST:REAM when applied to the Afon Einon using levels of explanation of 5% and 10%, respectively in the zonation procedure.

It is apparent that, by decreasing the scale of the reaches within the ST:REAM representation of the Afon Einon, some of the reaches identified by Henshaw in Figure 7.8 that were not recognised by the original ST:REAM model become defined. For example, rather than being one single reach with a high CSR (Figure 7.12), the main stem of the Afon Einon upstream of the confluence with the Nant Gelli-Gethin is defined as having some short reaches within it that have low CSRs (points A1, A2 and A3 in Figure 7.15A). This is supported by the observations represented in Figure 7.8. Further, increasing the level of explanation within the zonation algorithm allows ST:REAM to predict the CSRs of multiple reaches within the tributary branches of the Afon Einon catchment.

Application of ST:REAM to the Taff catchment displayed in Figure 7.9 resulted in far more reaches than the application to the Afon Einon catchment, largely due to the difference in catchment size as the zonation algorithm was applied to the same level of explanation within both catchments. Therefore, it is useful to identify the impact that increasing the level of explanation in the zonation algorithm would have on the ST:REAM representation of the Taff catchment. Figure 7.16A displays the CSRs output from ST:REAM when applied to the Taff catchment using a level of explanation of 5% within the zonation algorithm.

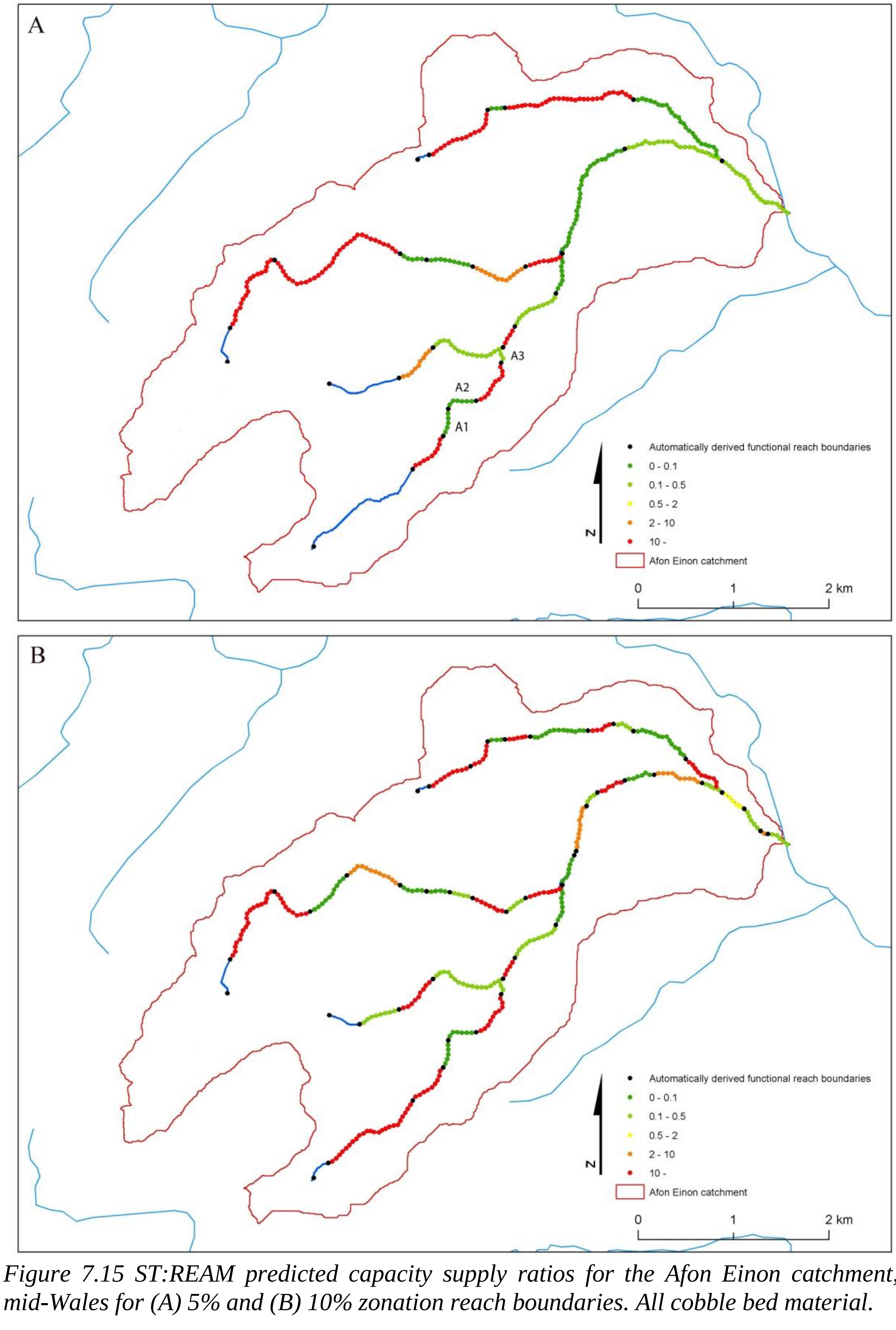


Figure 7.15 ST:REAM predicted capacity supply ratios for the Afon Einon catchment, mid-Wales for (A) 5% and (B) 10% zonation reach boundaries. All cobble bed material.

The observed sediment statuses displayed in Figure 7.6 were undertaken specifically for the reaches identified by the zonation algorithm at a 1% level of explanation of the total variation. This makes it difficult to make direct comparisons to the ST:REAM outputs obtained when using a level of explanation of 5%, because changing the level of explanation alters both the number of reaches and their boundaries. However, one observation that contributes to the assessment of the impacts of scale on ST:REAM can still be made. Based on examination of aerial imagery, certain sequences of reaches in Figure 7.16A that are predicted as having alternatively high and low CSR values actually correspond to lengths of channel dominated by riffle and pool bedforms, respectively (e.g. Figure 7.16B). In this sequence, riffles were identified as relatively steep, high transport capacity reaches with CSRs greater than 10, while pools were identified as relatively low transport capacity reaches with CSRs below 0.1. One of several examples of this phenomenon is displayed in Figure 7.16B. Increasing the level of explanation that the zonation algorithm provides results in the individual elements of the riffle-pool sequence automatically being delineated as individual reaches. This is not ideal because, in a catchment-scale assessment any continuous or semi-regular riffle-pool sequence should constitute a continuous, 'functional' reach. Hence, it is concluded that, in the Taff case study, reach delineation provided a better basis for analysis of sediment dynamics when ST:REAM was run using the 1% zonation algorithm (Figure 7.11).

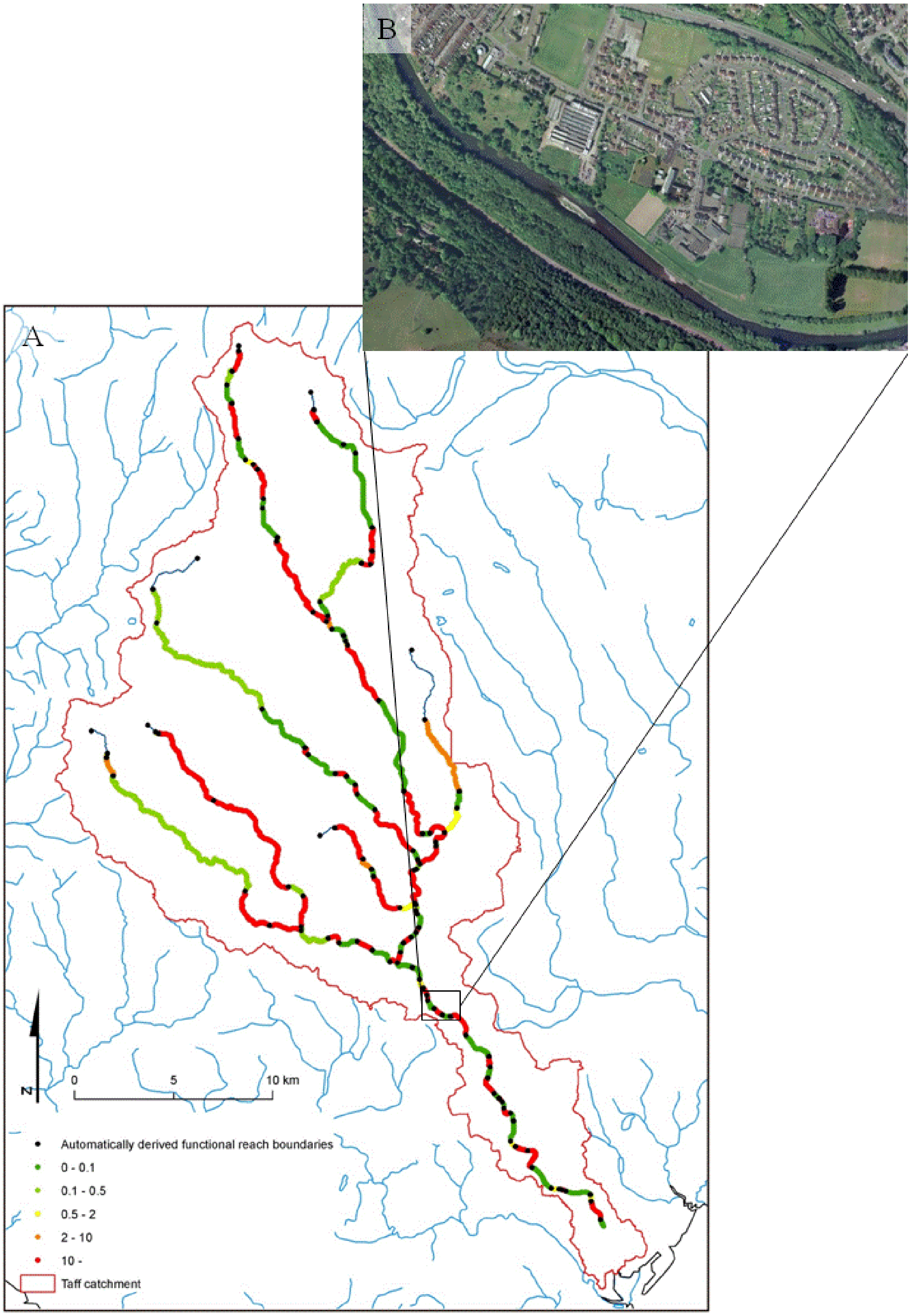


Figure 7.16 (A) ST:REAM predicted capacity supply ratios for the River Taff catchment, South Wales for 5% zonation reach boundaries. All cobble bed material. (B) Aerial image of riffle-pool sequence identified as separate reaches within the 5% ST:REAM model of the Taff catchment. Taken from Google (2009).

The findings reported in this section raise a key, but complex issue that concerning the most appropriate scale for the reaches to which ST:REAM is applied. This is important because calculated stream power per unit bed areas, and therefore sediment transport capacities, vary with the scale of consideration. The importance of scale can be demonstrated using contrasting examples from opposite ends of the scale spectrum. At the broadest scale, it has been proposed that, along the main stem branch in a fluvial system, stream power tends to peak in the middle of the basin (Lawler, 1992a; Lawler *et al.*, 1999). This is because, along the main stem (or in fact any individual branch), discharge (Q) increases according to a power relationship of downstream distance (L)

$$Q = k \cdot L^m$$

Equation 7.1

while slope (S) decreases according to an exponential relationship with distance downstream from an initial slope (S_0)

$$S = S_0 \cdot e^{-rL}$$

Equation 7.2

Combining these relationships indicates that stream power should vary according to the function:

$$\Omega = a \cdot L^b \cdot e^{-rL}$$

Equation 7.3

As a result, stream power peaks at an intermediate location within the catchment, the precise location depending on the values of the exponents m and r.

The equations proposed by Lawler (1992a) were used to generate curves of stream power and, hence, sediment transport capacity for the mean annual flow with a uniform sediment diameter of 0.1m along the main stems of the Afon

Eionon and the River Taff (Figure 7.17). As expected the proposed discharge and slope result in a smooth curve with mid-basin peak in stream power and, therefore, sediment transport capacity, in both catchments. However, also plotted in Figure 7.17 are sediment transport capacities predicted using local values of slope and discharge spaced at 50m intervals. It is immediately apparent that, in both catchments, local variability in predicted transport capacities dwarf any broad, basin-scale trend, if a basin-scale trend is actually present at all.

The obvious contrast between predicted basin-scale trends and measured local variations in sediment transport capacity emphasises the importance of scale to catchment-wide assessment of sediment dynamics. The exercises reported here have shown that application of ST:REAM using reaches explaining 1% of the total variation in sediment transport capacity produces sediment status predictions that are congruent with sediment statuses observed in the field. Decreasing reach scale and using reaches that explain 5% or 10% of the total variation in sediment transport capacity can help explain even more of the observed variations in sediment status. However, as for the Taff, increasing the level of explanation used in the zonation algorithm can also result in reaches being identified that are not of interest within the context of catchment-scale sediment dynamics. A potential means of addressing this issue would be to attempt to scale the zonation procedure on channel width so that short reaches could be identified in low order channels with narrow channels, without wider, higher-order channels being divided into reaches of the scale of local bar forms. Despite investigation to identify a way of scaling the reach delineation method on channel width, no means of achieving this consistently could be identified in the course of this research project.

It is concluded that, unless a means of scaling the reach zonation algorithm against channel order or width can be successfully developed, ST:REAM should be applied using reaches explaining just 1% of the total variation in transport capacity. Whilst currently this limits ST:REAM to assessing broad-scale variations in coarse sediment transport capacity, this is a reasonable compromise that is also necessary to avoid ambiguities that arise when attempting to identify reaches at finer scales.

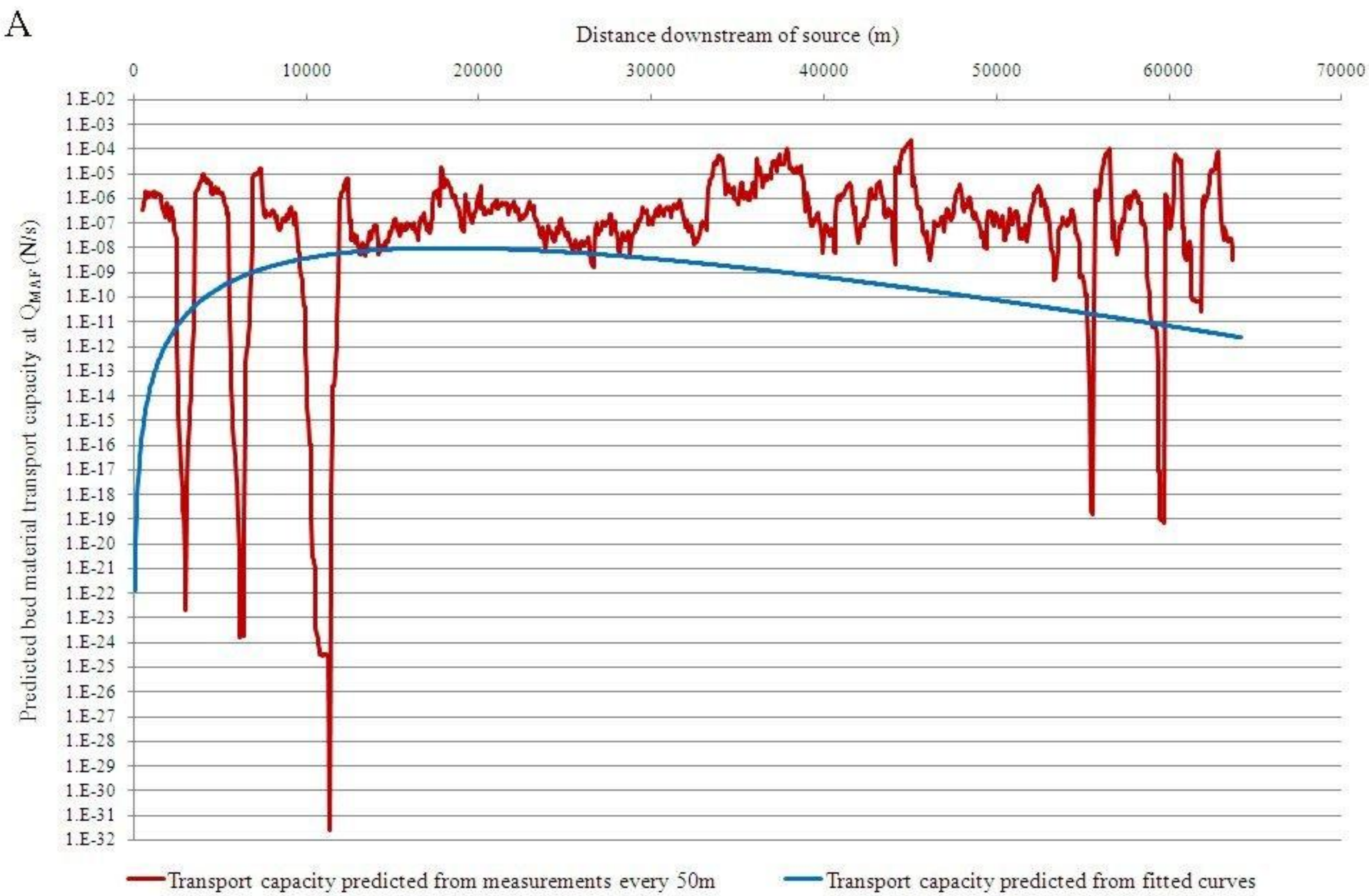


Figure 7.17 (A) Local vs. Catchment trends in sediment transport capacity within the River Taff catchment, South Wales.

B

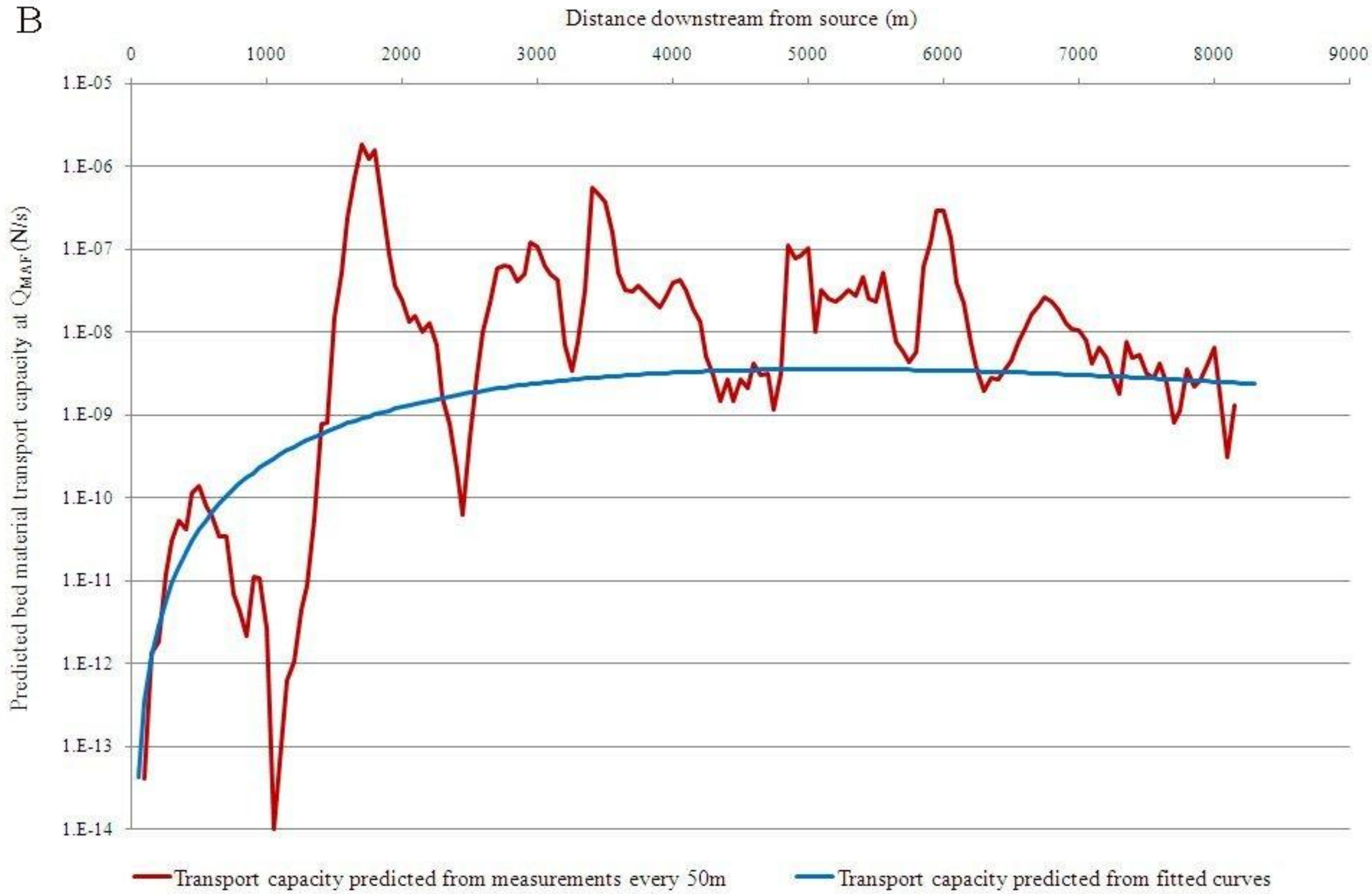


Figure 7.17 (B) Local vs. Catchment trends in sediment transport capacity within the Afon Einon catchment, mid-Wales.

Chapter Eight: Applications, Implications and Conclusions

8.1 Applications within river management

ST:REAM has potential applications within multiple aspects of river and catchment management. As identified within Chapter Two, it has become increasingly clear that sediment dynamics must be taken into account in flood risk management because scour, deposition, morphological change and related habitats all have significant impacts on flood conveyance capacity and the performance/stability of flood defence infrastructure. There are various ways in which ST:REAM can be applied to support consideration of the implications of coarse sediment dynamics and their management for integrated flood risk management. The first issue described here is identification of appropriate locations for removal of excessive sediment deposits.

As has been demonstrated by Lane *et al.* (2007), in reaches which lack the capacity to transfer the sediment that is supplied to them, within-channel sedimentation can reduce channel flood capacity and increase the frequency and magnitude of out-of-bank flows. Sear *et al.* (1995) described how a large proportion of the maintenance activity performed in ensuring British river channels can convey their flows is dedicated to the removal of excess bed sediment deposits through dredging, de-silting and shoal removal. Dredging is the removal of sediment that has accumulated in the channel to a degree that is considered to compromise flood defence or land drainage functions of the channel; de-silting is the removal of sediment that has recently accumulated in the channel; and shoal removal is the removal of individual bars and bedforms where these are considered to compromise the flood control function of the channel (Sear *et al.*, 2003). A combination of financial restrictions and concerns regarding the ecological impacts of sediment removal limits the total amount of sediment-related maintenance that can be performed and so it is important that efforts are targeted on the locations where it is of most benefit. Currently, these locations are identified on the basis of stakeholder pressure, experience and past practice, with little or no regard to whether the cause of the problem is local or is a symptom of an imbalance in the sediment transfer system. ST:REAM provides a scientifically-based means of identifying reaches with low CSRs, where excessive deposition is likely due to imbalance in the coarse sediment transfer system. In these cases, sediment removal is unlikely to provide anything but a temporary solution and river managers can use ST:REAM to investigate how the wider cause of the sedimentation problem might be addressed sustainably. Conversely, where deposition that poses unacceptable flood risks to people or property has a local cause that is unrelated to imbalance in the coarse sediment transfer system, bed sediment removal may be justified and effective.

ST:REAM also has the potential to provide outputs that are useful to the management of river habitat. It is recognised that the sediment transfer system plays an important role in shaping the physical biotopes and functional habitats present within stream channels. Excessive siltation resulting from the inability of a reach to transport the sediment supplied to it or artificial elevation of that supply can reduce habitat quality and adversely impact the reproductive cycle of those fauna who spawn within gravel substrate (Harper and Everard, 1998; Soulsby *et al.*, 2001; Hendry *et al.*, 2003). Conversely, excessive erosion resulting from excessive transport capacity or sediment starvation can also damage physical habitat due to scouring of the bed or accelerated bank retreat. ST:REAM can provide a means of identifying reaches within a catchment where excessive siltation or erosion are likely to damage habitat quality so that either restorative or mitigating actions can be taken.

Outputs from ST:REAM can also provide an explanatory variable to ecologists concerned with riverine species distributions and promoting biodiversity. Whilst it is recognised that coarse sediment dynamics are important in influencing physical habitat, and therefore in-stream ecology, there have been difficulties in parameterising the influence of geomorphological processes within models predicting species diversity (Ian Vaughan, University of Cardiff, personal communication, 2009). The outputs from ST:REAM can provide an indication of likely morphological status across entire catchments, which can be compared against national species distributions datasets and used to add explanatory power to existing models for predicting species diversity.

The European Water Framework Directive has set targets for the improvement of the hydromorphological status in water bodies by 2015 (EU, 2000). To facilitate these improvements in British rivers, it is first necessary to identify the locations in a catchment where 'hydromorphological' improvement is most likely to successfully lead to an improvement in ecological status. Given the operational scale at which these improvements are necessary, and the time and budgetary constraints within which they need to be made, ST:REAM provides a rapid means of identifying reaches within a catchment that are of poor hydromorphological status due to excessive erosion or deposition driven by sediment imbalance in the fluvial system. This information could assist in the prioritisation of river reaches with respect to implementation of Programmes of Measures (POMs) proposed in the relevant River Basin Management Plan that are intended to trigger hydromorphological improvements through, for example, river restoration.

ST:REAM could be useful not only in identifying the reaches within a catchment that may be in need of hydromorphological enhancement or river restoration, but also in the context of enhancement or restoration design. Soar (2000) described how successful river channel restoration depends on ensuring that the newly designed channel does not disrupt sediment transfer within the catchment, either by supplying more sediment than the channel downstream can transport, or by failing to transport the sediment that is delivered from the channel upstream. The impact of proposed channel enhancement or restoration designs on coarse sediment dynamics can be simulated using ST:REAM in order to identify the design that provides the least disruption to transfer continuity and connectivity within the catchment.

Whilst the specific applications outlined above represent potential valuable uses of the ST:REAM approach within British river management, the most useful role for ST:REAM is not to solve any one specific type of management issue, but instead to provide a broad understanding of the state of the catchment as a sediment transfer system. Understanding not only which reaches are sediment sinks and which are sediment sources, but also whether that status is an outcome of the natural operation of the sediment transfer system, the unintended result of poor management, or the impact of an anthropogenic pressure is important for any river manager seeking to manage a catchment holistically and sustainably. This is why geomorphology was identified as a key component of the Environment Agency's Catchment Flood Management Plans (CFMPs) and River Basin Management Plans (RBMPs). However, as identified at the outset of this study, there is currently no means of considering sediment dynamics as they operate throughout a catchment due to data and operational constraints. ST:REAM can go some way to filling this gap so that aspects of sediment transfer are more easily considered within catchment-level river management. In fact, due to its relatively low data requirements, such is the ease with which ST:REAM can be applied, it is envisioned that it could produce outputs of predicted sediment status for reaches within *every* British river catchment, for inclusion in the next generations of CFMPs and RBMPs. It is this potential to produce a representation of predicted broad-scale sediment dynamics nationally that is the primary strength of the ST:REAM approach.

Despite the potential for ST:REAM to contribute a useful tool within river management, it is important to recognise its limitations within any application. ST:REAM provides a means of quantitatively predicting the sediment continuity for reaches within a catchment network. However, this prediction is based on many simplifications of what is inherently a complex, non-linear, dynamical system. The majority of these simplifications and the justifications for them are described in detail throughout Chapter Four, but in summary ST:REAM:

i. treats bed material size as a dependent variable, allowing the simplification that the characteristics of coarse sediment in transport are uniform and can be represented by a single grain size throughout the catchment;

ii. calculates reach transport budgets based on predicted bed surface material transport capacity, rather than either predicted bed-load or even predicted bed material transport capacity;
iii. does not account explicitly for coarse sediment supplied to a reach from sources other than the reach(es) (either along the same branch or from a tributary) directly upstream;
iv. assumes that, unless a reach is identified as having non-erodible boundaries, the sediment output from a reach is equal to its transport capacity;
v. divides the drainage network into reaches, within which channel form and processes are uniform, but between which they change abruptly;
vi. offers a static representation of a natural system that is inherently dynamic, with no attempt made to simulate non-linear interactions which over time can result in morphological behaviours not represented in this reach-based sediment-balance approach;
vii. cannot provide a sediment status classification for the furthest upstream reach on each branch because of a lack of upstream neighbour from which to calculate the capacity supply ratio.

In making simplifications of naturally occurring processes, ST:REAM is no different from any other sediment model; however in addressing the significant data input restrictions imposed upon its design, it is inevitable that ST:REAM has made more simplifications than other, less widely applicable, models. As a result of these simplifications, it is important that the outputs from ST:REAM are never used in isolation to support decision making in river management. Instead, it is recommended that the outputs from ST:REAM are used alongside, or in conjunction with, other observations and calculations of sediment dynamics within the catchment under consideration. At the very least, this should take the form of a field and desk-based reconnaissance to gain a qualitative understanding of the sediment processes operating with the catchment, and close examination of aerial imagery, to identify whether the outputs of ST:REAM are supported by observations of reach-scale morphologies. As was recognised within Section 7.3, this type of remotely-sensed reconnaissance can also be useful in ensuring that the model inputs are appropriate, particularly the identification of high energy reaches with non-erodible boundaries.

The version of ST:REAM presented and assessed herein should not be considered ready for uptake within river management. As emphasised in Section 7.2, the model assessment process performed as part of this doctoral research did not, and could not, validate ST:REAM as being fit for use in accounting for catchment-scale coarse sediment dynamics for river management purposes. The assessment process did, however, establish that ST:REAM can produce outputs that generally correspond to the observations made in two test catchments, as well as identifying the sensitivity of model outcomes to changes in user-defined factors that affect the performance of the model.

A significant limitation of the assessment of ST:REAM performed in Chapter Seven is that it was performed on just two test catchments, both of which are representative of the same river type - steep, gravel-bed rivers. This small sample size is justified given the scope of this study. However, it means that not only is ST:REAM not completely proven within steep gravel-bed rivers, but that ST:REAM has not been tested at all against other river types. Whilst the same general theories can often be used to explain all different river types, exactly how those theories apply to a river can depend upon the type that river falls into. For example, hydraulic geometry, as developed by Leopold and Maddock (1953), may be relevant to all rivers, but the actual nature of those hydraulic geometry relationships varies across river types. It is therefore possible that a chalk-bed stream typical of south-east England, or a large sand bed river like the lower reaches of the River Severn, would behave differently to the Taff and the Einon when modelled within ST:REAM.

As a result, it is recommended that further assessment of ST:REAM should be performed across a wider range of test catchments to ensure that its outputs are equally representative across all British rivers. It is anticipated that the model will struggle to produce representative outputs in bedrock dominated rivers. This is because, in this type of system, the assumption that ST:REAM makes regarding the output from a reach being equal to its transport capacity will be particularly invalid.

A further limitation of the assessment performed in Chapter Seven is the form of the data used to 'ground truth' the outputs from S:TREAM. As would be expected given the reasons behind the aim of this thesis, there exists no easy method for identifying the sediment status of river channels. The only means by which the outputs from ST:REAM could be assessed at the catchment-scale was to compare them to sediment status as decided by expert judgement. Clearly, this type of assessment is dependent on the assumption that the so-called 'expert judgement' provides an accurate and comprehensive representation of the sediment status across the catchment. Along with the questionable assumption that expert judgement can correctly identify the sediment status of a channel at a given point, in testing ST:REAM on both the Einon and the Taff there are specific reasons why sediment status throughout the catchment may not be appropriately represented.

As described in Section 7.3.2, the sediment status of the Einon catchment was described based on the experience of a researcher who had spent four years studying its sediment dynamics (Henshaw, 2009). Their expert judgement was used to divide the catchment into a series of independently assigned reaches and allocate a sediment status for each reach. The main assumption made by this process is a reflection of one of the key assumptions of reach-based models – that rivers can be appropriately divided into a series of homogenous reaches. In reality, natural rivers vary across a range of scales and therefore even if functional reach boundaries can be assigned correctly it is likely that some variation in sediment status will occur within a 'homogenous' reach. This is not reflected either by the outputs of ST:REAM, or by the datasets upon which those outputs have been assessed.

Given the scale of the Taff catchment, expert judgement on the sediment status of the catchment was achieved by observing the river channel at a finite number of points throughout the catchment. In order to ensure that a decision could be made on the status of each of the catchment's reaches, the observation points were stratified so that at least one fell within each reach. This stratified sampling of observations makes two questionable assumptions. Firstly, it assumes that the functional reach boundaries identified by Gill's (1970) zonation algorithm has appropriately identified the functional reach boundaries within the river catchment. Since the ground-truthing observations are based upon boundaries that ST:REAM itself has derived this represents a degree of circularity in the assessment process. Secondly, it assumes that the points at which the river channel is observed are representative of the entirety of the functional reach that they falls within. This second assumption is linked closely with one of the assumptions of the assessment of ST:REAM on the Einon catchment – that rivers can be appropriately divided into a series of homogenous reaches. These assumptions were both necessary given the difficulty in obtaining alternative measures of sediment status at the catchment-scale and scope of this study.

As a result of these limitations it is suggested that, in order to comprehensively assess the performance of ST:REAM, it is necessary to compare its outputs against a continuous representation of channel sediment status throughout an entire catchment. As identified at the outset of this thesis, there is a difficulty in doing this given the data currently available. However, it is possible that repeat LiDAR surveys over medium time-scales (10-50 years) could be used to identify morphological change at the catchment-scale. It is proposed that when this data becomes available it would provide a useful dataset against which to compare the outputs of ST:REAM.

On a related point, future technological developments will likely lead to an increase in the quantity, quality, and variety of catchment-scale datasets available to river managers. As a result this will relieve some of the restrictions imposed upon the development of ST:REAM as a catchment-scale model of sediment dynamics. Recognising these improvements in data availability and updating ST:REAM accordingly is an important process that will ensure the model's progression.

Finally, further development of ST:REAM should focus on improvement of its user interface. In addition to ensuring that ST:REAM is widely useable given currently available datasets, and that it produces scientifically credible and practically useful results in order to promote its uptake amongst the British river management community, it is important that it is easily applied. Currently, ST:REAM is based within a Microsoft Excel spreadsheet and requires the user to obtain and enter all of the input data manually. It is envisaged that the entire process could be automated if ST:REAM were to be based within a GIS environment. Given the appropriate MasterMap, DEM, drainage area, annual potential evaporation, annual rainfall, and RHS layers, ST:REAM could automatically derive all of the input data for a specified catchment and produce the resultant outputs in a single action.

8.2 Implications for river research

The ST:REAM model that is the major outcome of this thesis, together with the more general findings reported here, have implications for further progress in the theoretical understanding of sediment dynamics that underpins scientific fluvial geomorphology. This was identified as a potential consequence of the research to be performed in this study at the outset (see Section 1.2). The research and theoretical implications stem from consideration of how the major components of the ST:REAM model (including the new, general sediment transport equation) can inform future research initiatives in various aspects of river science, and also how the overall approach developed and adopted can influence thinking on how sediment dynamics link process-form and process-response behaviours operating in the fluvial system at the micro-, meso- and catchment-scales.

8.2.1 Applications of functional reach boundary hunting algorithms

The research efforts documented in Chapter Five resulted in an objective method for automatically identifying reaches within a river network that are internally homogenous relative to each other and which are, therefore, comparatively distinct. This type of methodology has implications not only for existing sediment transport and balance models that rely on user-defined reach boundaries, but also as a means of identifying functional reach boundaries for researchers interested in studying any aspect of spatial organisation in a river network. For example, researchers at the University of Southampton have recently applied a boundary hunting algorithm different to that used here to identify functional reaches within a model designed to assist decision making for fishery management (Marc Naura, University of Southampton, personal communication, 2009).

The potential implication of the work carried out in Chapter Five is that the subjective setting of reach boundaries based solely on field or desk reconnaissance coupled with specialist interpretation and judgement is no longer defendable as a way of dividing up the fluvial system. While well-informed, expert opinion will always be valuable, Chapter Five suggests that it should be applied alongside the type of objective boundary hunting methods reported and tested here whenever it is necessary to divide a river network into reaches. However, before zonation algorithms can be confidently applied widely throughout river catchments it is necessary to test their performance more thoroughly. Chapter Five proposed zonation algorithms as a means of objectively dividing catchments into reaches, tested a selection of zonation algorithms against each other and demonstrated the value of their implementation. However, the testing of the algorithms described in Chapter Five was limited to main stem of the River Taff in South Wales. Whilst the River Taff is not atypical of British rivers in general, it is only representative of a certain type – medium sized, steep, gravel-bedded rivers punctuated by bedrock. Further, it did not test the performance of the zonation algorithms against expert opinion, nor did it test whether multivariate zonation algorithms might provide a better definition of reach boundaries. Clearly, an important and interesting line of future research lies in assessing and developing the zonation algorithms proposed in Chapter Five.

8.2.2 Advance towards a general bed material transport formula

The bed material transport formula derived in Chapter Six by no means represents an end point in the quest for a general solution to the sediment transport problem, but some aspects of its development represent significant contributions to the sediment transport knowledge base. In particular, Section 6.4.1 identified that, despite tractive force being the parameter that dominates the recent literature on sediment transport, unit width or stream power per unit bed area is more closely and consistently correlated with sediment transport rate in the very large data collection examined in this study. Stream power per unit bed area can be expressed as the product of bed shear stress (that is: tractive force per unit bed area) and mean velocity and therefore essentially acts to combine their effects in a similar manner to that suggested by Mavis and Laushey (1949). It was therefore argued in Section 6.5.1 that its representation of the *combined* influence of both velocity and tractive force is responsible for the strong statistical association between sediment transport and stream power per unit bed area. Further, since stream power per unit bed area is easily calculated using gross channel parameters, it represents an extremely practical means of predicting transport rates.

Another original contribution reported in Chapter Six was the discrimination between the transport of material observed on the surface of the bed and the transport as bed-load transport of other sediment sizes, finer than those found on the bed surface. No totally objective means of differentiating between sediment fractions that are and are not present on the bed surface has yet been defined. However, it has been demonstrated that it is useful to account for the fact that measured bed-load consists of both the fractions representative of the known bed surface and finer fractions whose transport rates are difficult to measure and predict. Further work is necessary to attempt to formalise a methodology for differentiating between the transport of bed surface material fractions and those, potentially supply-limited, finer fractions that make up the remainder of the transported bed-load.

Identification and quantification of separate ‘competence’ and ‘capacity’ phases of bed material transport represents a further, original contribution to studies of sediment transport. Whilst Barry (2007) had suggested the presence of a third phase of transport in addition to the conventionally accepted Phases I and II, his treatment was largely theoretical. The relationship presented in Figure 6.8 and

Equation 6.23 therefore represents a first attempt to quantify these transport phases. In order to fully understand the nature of coarse material transport further work is necessary to test the relationship illustrated by Figure 6.8 across a wide range of flow conditions.

Perhaps the most significant contribution in Chapter Six is, however, integration and editing of bed-load transport datasets from a wide range of environments to produce a single very large, but internally consistent dataset and bed surface material transport function (Figure 6.8 and Equation 6.23). It is anticipated that this 'general' relationship will be particularly useful in research applications where indicative, quantitative predictions of transport capacity are required, but their precision is not the primary concern. A unique feature of the general equation derived here is that it can be applied without knowledge of the depth-velocity relationship for the flow: Bagnold's original stream power-based equations (Bagnold, 1977; Bagnold, 1980; Bagnold, 1986) require some representation of flow depth as this is related to critical stream power and the efficiency with which stream power is used to transport sediment. Avoiding the requirement to know the depth and mean velocity improves the ease of application of the relationship displayed in Figure 6.8 and expressed in Equation 6.23 beyond that of any of the currently available sediment transport equations.

One important limitation of the transport relationship illustrated in Figure 6.8 and described by Equation 6.23 is that it is a *bed surface material* transport relationship. Isolating the bed surface material from the potentially supply limited finer fractions did make it easier to define a generally consistent relationship but it does mean that the transport relationship derived ignores all material finer than that observed on the bed surface and therefore is actually just for bed surface material – not for bed-load or even bed material. Whilst this limitation should be taken into account during its application, it should not inhibit the intended function of the derived transport relationship – which is a generally applicable formula that provides indicative, not absolute, predictions of sediment transport capacity. Nevertheless, in order to develop formulae that can predict total bed-load transport it is necessary to develop techniques that can accurately measure and predict the transport of the finer, often supply-limited, bed-load fractions.

8.2.3 Time, space and causality of bed material size

An interesting and somewhat unexpected finding of this study was that incorporating spatial variation in bed material sizes in a ST:REAM assessment of catchment-scale sediment dynamics did not improve, and actually reduced, agreement between predicted and observed reach-scale sediment balance status. This outcome can be partially attributed to the limited resolution, precision and accuracy of the data used to represent bed material variability, despite them being the best that could reasonably be expected at the catchment-scale for British rivers. However, this finding also resonates with a debate regarding causality in catchment-scale sediment dynamics over steady-state time-scales that was considered in Sections 4.5 and 7.4.2 and which centred on whether bed material size is a dependent or independent variable with respect to coarse sediment dynamics.

Any debate regarding causality in the fluvial system must start with reference to 'Time, space and causality in Geomorphology' by Schumm and Lichty (1965), which was seen by many as a means of satisfying the arguments of both the 'historical' and 'process' approaches to the study of landforms (Kennedy, 1997). Within their paper, Schumm and Lichty argued that the distinction between cause and effect in the evolution of landforms depends upon the span of time involved and on the size of the geomorphic system under investigation. As the dimensions of time and space change, the causality of relationships between factors of interest in the physical landscape can be obscured or even reversed, so that relationships between processes and forms in the newly scaled system must be described differently (Schumm and Lichty, 1965). However, at no point within their paper do Schumm and Lichty (1965) consider the causality of relationships that should be ascribed to bed material size.

Bed material size is generally viewed as an independent variable within reductionist approaches to sediment dynamics because of the influence that it has on the rate at which sediment is transported along a channel. However, whilst a range of historical and geological factors influence the type and size of material observed on the channel bed in a river reach, Section 4.5 identified that a significant influence is the transport capacity of the reach in relation to the sediment size distribution supplied to it from upstream. For example, steep, high energy reaches have coarse bed material because the finer fractions of sediment delivered to them from upstream are easily transferred downstream. This finer material travels quickly through the fluvial system until it enters a reach with less energy, where it becomes incorporated into the bed material and progresses downstream at a much slower rate. Based on this line of argument, a modified version of Schumm and Lichty's (1965) table of causality for river variables is proposed in Table 8.1 where the suggested explanatory status for bed material size has been added. It is this line of argument that supports the assumption made within ST:REAM that bed material size is a dependent factor within catchment-scale sediment dynamics, at least when considered within a uni-directional approach and over steady-state time.

Lane and Richards (1997) argued that Schumm and Lichty's (1965) concept of different scales of form and process being causally independent of each other is unsustainable because processes operating at short time-scales and small space-scales influence those operating over longer time-scales and larger space-scales. Their line of argument was well demonstrated using data from a braided reach of the actively changing Borgne d'Arolla River in the Swiss Alps, where the longer time-scale and larger space-scale evolution of a medial bar was found to be controlled by the effects of shorter time-scale and smaller space-scale processes, which themselves evolved through feedback processes (Lane and Richards, 1997). However, this criticism of Schumm and Lichty's (1965) separation of causality at different scales is unhelpful if it is over-emphasised, especially as the identification of non-linear behaviour within fluvial systems is difficult (Montgomery, 1993), and the full implications of non-linear thinking for geomorphological understanding have yet to be assessed (Lane and Richards, 1997; Phillips, 2003).

Like all abstractions of reality, Schumm and Lichty's (1965) system for identifying causality at different scales in geomorphology represents a simplification of the complex interactions and feedback loops that operate within natural systems. This particular simplification enables fluvial geomorphologists to visualise those processes that operate most effectively at a specific scale, while ignoring the complications associated with feedback mechanisms referred to by Lane and Richards (1997) that may not be particularly important at that particular space-time scale. Whilst it must be recognised that the response of the system to an imposed process event depends on the 'conditioning' effect of previous events (Newson, 1980), and that events occurring at different time- and space-scales may have a net 'configurational' effect upon the system (Simpson, 1963), it is still often necessary to be able to simplify the complexity inherent in natural systems in order to understand and represent them holistically. For example, it was recognised in Section 4.5 that, in reality, bed material size is the net result of complex, spatially distributed form-process feedbacks between: local flow hydraulics, bed roughness and sediment mobility; reach-scale sediment transport processes, flux imbalances and channel morphology, and the stochastically-controlled and physically indeterminate delivery of sediment to the drainage network from catchment sources external to the river. However, it is neither necessary nor, in practice, possible to represent these interactions and stochastic inputs in a static, steady-state treatment such as a reach-based sediment balance model. Accepting this, it becomes clear that the bed material size should be treated as a dependent variable when assessing coarse sediment dynamics at the catchment-scale over steady time. However, whilst bed material size is best modelled as uniform within an approach like ST:REAM, as it deals with sediment balances rather than actual sediment fluxes, where users wish to predict sediment fluxes it *is* necessary to account for bed material sizes, as is done so in sediment routing models.

Table 8.1 The status of river variables during time-spans of decreasing duration. Modified from Schumm and Lichty (1965).

River Variables	**Status of variables during designated timespans**		
	Geologic	**Modern**	**Present**
Time	Independent	Not relevant	Not relevant
Geology	Independent	Independent	Independent
Climate	Independent	Independent	Independent
Vegetation	Dependent	Independent	Independent
Relief	Dependent	Independent	Independent
Long-term discharge of water and sediment	Dependent	Independent	Independent
Valley dimension (width, depth and slope)	Dependent	Independent	Independent
Mean discharge of water and sediment	Indeterminate	Independent	Independent
Channel morphology (width, depth, slope, shape and pattern)	Indeterminate	Dependent	Independent
Observed discharge of water and sediment	Indeterminate	Indeterminate	Dependent
Observed flow characteristics	Indeterminate	Indeterminate	Dependent
Observed bed material	*Indeterminate*	*Indeterminate*	*Dependent*

8.2.4 Evidence for non-equilibrium and spatially-distributed form-process feedbacks within downstream trends in transport capacity

Section 7.4.3 identified dramatic differences between the downstream variation in stream power and transport capacity values along a river branch based on catchment-scale trends, and the downstream variation in stream power and transport capacity values derived from closely spaced, measured values. This demonstrates that broad-scale, downstream trends in coarse sediment transport capacity are dwarfed by local variations. Whilst *"the big question ... might open up new or enlarged areas of inference or association"* (Leopold and Langbein, 1963: 192), care must be taken when using general trends as a mode of explanation in fluvial geomorphology as *"the seductive quality of the trend may disguise order-of-magnitude local variability"* (Lane and Richards, 1997: 249).

The dominance of local variability over catchment wide trends emphasises the importance of the 'configurational' over the 'immanent' effects controlling sediment dynamics referred to in Section 8.2.3. Under experimental laboratory conditions that are independent of the complications introduced by climate, geology, vegetation and historical legacy effects, discharge, slope and width (and therefore transport capacity) may be expected to be closely related to downstream distance based on immanent physical processes. It is under this type of system that the hydraulic geometry relationships proposed by Leopold and Maddock (1953) would hold true. However, in real river systems inherent, natural variability coupled with the legacies of numerous past events (natural and anthropogenic) that have influenced and which go on interacting with contemporary processes means that the configurational state of a catchment inhibits the formation of a discernible, equilibrium pattern. Instead, within natural systems, where configurational factors disrupt smooth, downstream trends, a continuously varying model of hydraulic geometry like that developed by Rhoads (1991) is more appropriate.

Phillips (2009) is one of many scholars to have identified the contradiction between the theoretical equilibrium states identified as being the idealised, end-point of fluvial system development and the scarcity of examples of systems that exhibit signs of being in or near their equilibrium state. Both of the catchments explored in Chapter Seven constitute examples of systems that are not in an equilibrium condition. Physical processes may cause a catchment's morphology to move towards an equilibrium state, as the erosion within high energy reaches reduces their slope and deposition in low energy reaches raises local bed elevations but, inevitably, some configurational influence (such as a geological control or climatic change) will either inhibit progress towards equilibrium (e.g. in the form of a bed-rock outcrop) or actively move the system away from equilibrium towards a new condition of dis-equilibrium (e.g. through a step change in precipitation).

The dominance of dis-equilibrium and non-linear, dynamical interpretations of spatially-distributed form-process feedbacks over equilibrium conditions is evident, and possibly exaggerated, in the outcomes of a ST:REAM application. For example, reach capacity supply ratios (CSR) output for the River Taff are in the range $2x10^{-13}$ to $8x10^{13}$ reflecting huge differences in calculated, annualised transport capacities between reaches. These large differences suggest non-equilibrium morphology in the channel network that is being exaggerated by configurational influences such as flow impoundment behind dams, construction of non-erodible, channelised reaches and geological controls in the form of bed-rock outcrops.

It is accepted that, by dividing the continuous river network sediment into a series of discrete reaches, ST:REAM acts to exaggerate the differences in transport capacity. In reality, changes in sediment balance status occur either gradually - as part of a continuum of adjustment in the morphological, roughness and bed material size attributes of the channel, or abruptly in association with a point sediment source or a distinct configurational control such as a dam. Notwithstanding this, the imbalances exaggerated by the reach discretisation process inherent to any reach-based method, including ST:REAM, cannot be dismissed and their presence in catchments that are typical of many British rivers is symptomatic of catchments dominated by the 'configurational' rather than the 'immanent'. These results are testament to the prevalence of dis-equilibrium processes and evolutionary forms over equilibrated processes and regime geometries – points of significance to all those who research, manage or seek to restore British rivers.

8.3 Conclusions

The research presented in this thesis began by reviewing the history of sediment research and management in rivers to develop the case and rational basis for a new approach to accounting for catchment-scale coarse sediment dynamics in British rivers. The research was motivated by the growing realisation that, despite coarse sediment dynamics playing an important role in affecting flood risk and habitat quality, the utility of the tools currently available for quantitatively accounting for coarse sediment dynamics is limited and, in practice, they are rarely deployed in British river research and management – both of which are largely conducted at the scale of the study site or project reach. Funding was provided by the EPSRC Flood Risk Management Research Consortium, to support a postgraduate studentship responding to the research needs associated with these issues.

A series of aims and objectives were set out, with the central goal being: *to develop and substantiate a new approach for quantitatively accounting for catchment-scale sediment dynamics in British rivers.*

In attempting to fulfil the aims and objectives set out at the beginning of this thesis, the research has identified why understanding and explaining coarse sediment dynamics is of fundamental importance to all aspects of river-basin research and management, how this importance is growing due to increased recognition of the process-form and process-response linkages that work across scales in the fluvial system and changes in how we manage and maintain British rivers so that they can continue to fulfil multiple functions (flood control, land drainage, navigation, recreation, fisheries, conservation) at time when anthropogenic pressures on them are increasing. Chapter Two addressed the first aim of this study by identifying the imperative for river researchers and managers to be able to account for catchment-scale coarse sediment dynamics in their work, and by reviewing historical progress made towards understanding these dynamics.

Based on an understanding of the research need, the research went on to identify and appraise both the sources of data of relevant to assessment and modelling of coarse sediment dynamics, and the approaches and techniques that are currently available to help understand and explain catchment-scale coarse sediment dynamics. The evaluation of the data sources and methodologies considered in Chapter Three demonstrated that a key constraint in the application of the majority of existing approaches is a lack of sufficient data. As a result, any new approach needs to be applicable using only data describing channel slope, discharge and width. A reach-based sediment balance approach was identified as the most appropriate model-type to allow a balance between scientific credibility and practical utility.

The requirements necessary to develop a new, reach-based sediment balance approach were identified at the outset of Chapter Four. Two of the more substantial requirements required for the development of the approach were addressed separately within Chapters Five and Six. These involved the development of a method for automatically delineating functional river reach boundaries and the synthesis of a general bed material transport relationship.

Based on the research outcomes reported in the preceding chapters, Chapter Seven presented the latest version of ST:REAM: a reach-based sediment balance model that quantitatively accounts for catchment-scale coarse sediment dynamics in British rivers whilst remaining practically applicable given the current level of data availability. The performance of the methodology developed within this study was explored through a progressive assessment process that was undertaken not only to identify whether ST:REAM can predict catchment-scale coarse sediment dynamics and the sediment status of individual reaches in the fluvial system accurately, but also to improve understanding of the factors influencing ST:REAM's performance and so aid further development. Testing against field and desk-based observations made within two test catchments established that ST:REAM can provide a reasonable representation of likely reach status. However, the accuracy of the outputs depends on multiple factors including, notably:

i. prior recognition of high energy reaches with completely non-erodible (generally concrete) boundaries;
ii. treatment of bed material size as uniform within a catchment; and
iii. setting the zonation algorithm used to identify reach boundaries so that the reaches explain 1% of the total variation in transport capacity.

Assessment of the ST:REAM methodology addressed the fourth aim of this study, although it is emphasised here that the progressive nature of the assessment process means that further development of the model is always desirable. The fifth and final aim, which involves considering the implications of ST:REAM for both the practical management of British river catchments and for academic treatment of coarse sediment dynamics, has been the focus of the preceding sections of this chapter.

Whilst this thesis has satisfied the aims set out in Chapter One, there have been a number of limitations with the methodologies applied in the development and assessment of ST:REAM. These have largely been recognised throughout the thesis but for clarity they are listed here:

i. This thesis has made the assumption that a steady-state and reach-based representation of the fluvial system is the most suited to catchment-scale representations of coarse sediment dynamics. This was based upon arguments made in Section 3.3.3 – that not only does dividing the drainage network into reaches simplify the complex hierarchy of forms and processes present in the fluvial system, but it also significantly reduces the data required to parameterise a model. However, Section 8.2.4 describes how, in reality, changes in sediment balance status can occur both gradually, as part of a continuum of adjustment, or abruptly, in association with a distinct configurational control. As well as sediment status varying at different rates and across different scales, Sections 2.5.8 and 8.2.3 describe how the fluvial system is controlled by a series of form-process feedbacks so that morphological variables are both driving and response variables. As a result of these observations, questions must be raised concerning the validity of using a steady-state, reach-based approach to represent a dynamic natural system.

ii. This thesis set out to develop a means of quantitatively accounting for catchment-scale sediment dynamics that could be applied by those responsible for catchment management. This meant that the developed approach had to be applicable using the data currently available to British river managers (the UK's Environment Agency). However, due to licensing restrictions not all datasets that are available to the Environment Agency were made available to this study. For example, both Low Flows 2000 and national LiDAR datasets are available to the Environment Agency but in this study an alternative FDC estimation technique had to be developed and LiDAR data could only be obtained for specific catchments. It is considered here that this limited the breadth of testing that could be applied within this study.

iii. As described in Section 8.2.1, the testing of the zonation algorithms used to divide catchments into reaches was limited to main stem of the River Taff in South Wales. It also did not test the performance of the zonation algorithms against expert opinion, nor did it test whether multivariate zonation algorithms might provide a better definition of reach boundaries.

iv. Section 8.1 describes how the assessment of ST:REAM was limited in two aspects. Firstly, it was performed on just two test catchments, both of which are representative of the same river type – steep, gravel-bed rivers. Secondly, the data used to 'ground truth' the outputs from S:TREAM were based on 'expert judgement' rather than an objective measurements describing sediment status or channel change.

Along with the questions answered as a result of this thesis, the research developments contained herein have also raised a number of issues that are worthy of further research. Again, a number of these have been raised earlier in this chapter but for clarity they are listed here:

i. As a result of the recognition that a reach-based steady-state approach may not necessarily be the ideal means of representing catchment-scale sediment dynamics, it is necessary to explore the potential for developing and assessing alternative approaches. One potential alternative is a cellular model similar to that described in Section 3.3.4 that is restricted solely to the river channels rather than the entire catchment. This type of model would allow catchment sediment dynamics to be represented in a more dynamic form.

ii. As identified by Section 8.1, future research efforts should be aimed at ensuring that both ST:REAM and alternative catchment-scale models of sediment dynamics evolve to take advantage of new and future developments in data gathering techniques.

iii. Section 8.2.1 identified that an important line of future research lies in the further development of zonation algorithms for identifying functional reach boundaries. Not only should the boundaries defined using a univariate zonation algorithm be assessed using boundaries defined by expert judgement, but also efforts should be made to develop multivariate zonation algorithms that can assist in the generation of reach boundaries suitable for inter-disciplinary research and management projects (as discussed in Section 5.9.2).

iv. A key area for further research is the continued assessment and development of ST:REAM as a model that can be applied by those responsible for river management. As a result of the limitations in the assessment of ST:REAM recognised above, it is necessary to test the outputs of ST:REAM against a wider range of catchments and using a continuous, objective measurement of channel sediment status. Section 8.1 identified that a potential means of deriving this continuous and objective measurement of channel sediment status is to use repeat LiDAR surveys to identify morphological change across a catchment.

It is hoped that future research efforts will act to provide closure to some of these issues, and as a result, advance on the contribution made by this thesis.

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Both Appendix A and Appendix B are included as digital appendices on the attached compact disc.

Appendix A: Collated bed-load transport datasets

This appendix consists of a Microsoft Excel 2003 workbook containing all of the bed-load transport datasets used to derive the bed surface material transport equation in Chapter Six.

Appendix B: ST:REAM version 5 – model with data

This appendix contains the latest working version of ST:REAM, the model developed and assessed within this thesis. The model is currently based within a Microsoft Excel 2003 Workbook, written in Microsoft Visual Basic for Applications. Included within the model is the input data required to run ST:REAM for the Taff catchment in South Wales.