A study of channel geometry - discharge relationships in semi-natural British rivers as a basis for river restoration and management.

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"The river looked at him with a thousand eyes - green, white, crystal, sky-blue. How he loved the river, how it enchanted him, how grateful he was to it ! In his heart he heard the newly awakened voice speak and it said to him: 'Love this river, stay by it, learn from it.' It seemed to him that whoever understood this river and its secrets would understand much more, many secrets, all secrets. But today he only saw one of the river's secrets, one that gripped his soul. He saw that the water continually flowed and flowed and yet it was always there; it was always the same and yet every moment it was new."

Hermann Hesse, *Siddhartha*

ABSTRACT

River restoration has developed over the last three decades in the context of a more holistic approach to river management. One of the most important issues facing river managers is the design of river channel dimensions. The successful design of cross-sectional dimensions requires an understanding of river channel stability and the sensitivity of rivers to change. A need for more work in this field was identified. This research investigates the variability of downstream channel geometry discharge as a basis for assessing river channel stability and sensitivity to change.

A national database containing 124 semi-natural UK river sites is used to develop a linear regression model relating bankfull width with dominant discharge. The magnitude and direction of standardised residual values from the model are then investigated in terms of their geomorphological significance. Particular groups of residual values are found to be related to specific controlling factors. Extreme high magnitude positive residuals (>1.0) are dominated by baseflow dominated chalk rivers. Negative residuals (>-0.5 to -1.0) are found to have a bedrock control. Other controlling factors operating at a local scale, including bank materials, bed materials and vegetation cannot be identified as having an exclusive influence on residual values. The variability in channel geometry - discharge relationships is broadly indicative of river channel adjustment based results from the field study of a subset of 50 sites. Residuals closest to the regression line demonstrate active or inactive stability and negative and positive residuals show a tendency towards erosional and depositional processes respectively. A study of temporal changes in a subset of 16 rivers supports these findings whilst highlighting the importance of the mutual adjustment of channel parameters through time.

To investigate river channel adjustment at a reach downstream within a single river, a more detailed catchment study forms the second part of the research. Three contrasting catchments were used to investigate the implications of changing downstream channel geometry and stability on river channel adjustment at a reach. The results reinforce the importance of assessing the mutual adjustment of width, depth, and gradient to identify the dominant form of adjustment at a reach. Drainage basin form was found to exert an important control on channel geometry adjustment both laterally and longitudinally downstream. The results support the findings from the national model which show that stability is a function of complex combination of controlling factors which are represented by the residual values. River channel stability can be viewed as a function of the flow regime related to local environmental factors. The variability of channel geometry - discharge relationships does appear to represent the direction of river channel adjustment, but stability at a reach must be evaluated in the context of the adjustment of downstream parameters related to both catchment and local scale controls.

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NOTATION

Ad	catchment area
Ab	bankfull channel capacity
d	mean bankfull depth
dmax	maximum depth
D_{50}	mean grain size
D_{84}	grain diameter at which 84 per cent of bed material is finer
D_{65}	grain diameter at which 65 per cent of bed material is finer
D_{90}	grain diameter at which 90 per cent of bed material is finer
DD	distance downstream
D_d	drainage density
ESTCA	estimated channel capacity
f	Lacey's silting factor
F_b	bed factor (Blench, 1969)
F_s	side factor (Blench, 1969)
g	co-efficient in slope-discharge relation
M	per cent silt clay in channel perimeter
P	length of wetted perimeter
Q	discharge
Q_p	individual flood peak
$Q_{1.5}$	discharge with a return period of 1.5 years
Q_2	discharge with a return period of 2 years
Qb	bankfull discharge
Qd	dominant discharge
Q_{maf}	mean annual flood
Q_{me}	most effective discharge
Q_s	sediment load
R	hydraulic radius
S	slope
S_b	bank silt clay content
S_c	bed silt clay content
T_p	return period of flow events
TCL	total channel length
V	velocity
V_o	non silting velocity
W	width
w	bankfull width
W:D	width:depth ratio
τ_c	critical shear stress

CHAPTER 1

INTRODUCTION

'In uninhabited regions the rivers are wayward and restless, ever shifting from place to place within the bounds of their valleys, that are theirs to sprawl across at will'

G.W. Lamplugh (1914)

1.1 Prologue

Natural river channels are free to adjust their shape and planform according to changing environmental conditions as they flow from the source to the sea. However, population growth associated with industrial and agricultural development, has led to increased demands on freshwater resources and the constraint of river channels and riverine environments. Channelisation, the artificial control of river systems through engineering for the purposes of flood alleviation, navigation and urbanisation (Brookes, 1988), has resulted in few rivers remaining in their natural condition, described so vividly by Lamplugh at the beginning of this century.

1.2 Channelisation of rivers in the UK: the status quo

Conventional engineering methods for channelisation involve resectioning, the enlargement of the channel through widening and deepening; realignment, the straightening of meandering rivers; regrading, bed-levelling often involving the removal of the pool-riffle sequence; and in extreme cases lining of the channel with rigid materials such as concrete. These procedures can cause significant geomorphological disruption to the river channel both during engineering works and for many years after. The repercussions of engineering works at any given location can be transmitted over a wide area especially in a downstream direction. Brookes (1987a) highlighted the importance of downstream changes occurring as a result of channelisation and in an investigation of 46 UK sites found that the majority of high energy channels that had undergone engineering had shown some form of erosive adjustments downstream from the channelisation works. For example, the River Aln was resectioned for a length of 7760m downstream from Abberwick in 1947 resulting in an 85% increase of the maximum capacity, extending 575m downstream of the engineered reach (Brookes, 1987a). Engineering at a single reach can cause problems both at the reach and upstream and downstream from the reach in terms of geomorphological instability, biological damage and aesthetic impacts.

The problems associated with conventional engineering were recognised during the 1970's in papers such as 'Channelisation; the search for a better way' (Keller, 1975) which advocated a new approach to river channel design to "incorporate channel form and processes that duplicate nature rather than create artificial conditions in channels". Brookes (1988) listed articles which reflected the degree of public concern surrounding river channelisation in the US; problems which became increasingly discussed in the UK during the 1970s and 1980s eventually leading to environmental legislation and revised methods of management. The idea of reproducing natural processes articulated by Keller (1975) and later by Leopold (1977), has been reflected in a more holistic approach to channel management working with rivers rather than against them (Brookes, 1988) to try and limit environmental damage.

Evolving from this holistic approach to river management, river restoration has developed as a method of reinstating more natural processes to river systems. Pioneered in Denmark during the 1980's, river restoration was introduced to the UK in the early 1990's with the establishment of the River Restoration Project (RRP) in 1992 (Brookes, 1995a). The project was initially based on two UK demonstration projects in the River Cole, Wiltshire, and the River Skerne, Northumberland, supported by European Union LIFE funding in partnership with Denmark. The RRP project led on to the opening of the River Restoration Centre based in Silsoe, Bedfordshire which, continuing from the work of the RRP, aims to encourage the exchange of information on the activities and initiatives relating to river restoration. The function of the centre is ultimately to enable practitioners to benefit and contribute to the developing expertise and knowledge in river restoration. The amount and extent of research on river restoration in the UK has increased throughout the decade, but there are still fundamental geomorphological questions that need to be addressed. The following section (1.3) will discuss the concept of river restoration and highlight some of the geomorphological issues that are crucial to the improvement of restoration philosophy and techniques.

1.3 River Restoration

A widely accepted definition of river restoration was presented by Cairns (1991) who described the process of restoration as "the complete structural and functional return to a predisturbance state". Whether a river can ever be restored to this state is questionable. It may not be possible or even desirable. Consequently, rehabilitation defined as "the partial structural and functional return to a pre-disturbance state", where the morphology of the bed or banks may be altered, without the complete redesign of the channel is more widespread. Enhancement is regarded as 'any improvement of a structural or functional attribute' (National Research Council, 1992,). For example, instream flow devices may artificially improve the river environment and allow flow patterns to assist with the recolonisation of certain plant species lost as a result of channelisation. The type of restoration determines the management approach (see table 1.1) and both must be decided upon at the beginning of any restoration project.

Table 1.1 The definition of types of river restoration and associated management approaches (Brookes and Shields, 1996, p.4).

Term	*Definition*	*Management approach*
Full restoration	The complete structural and functional return to a predisturbance state	Direct intervention or natural recovery
Rehabilitation	Partial return to a predisturbance structure or function	Direct intervention
Enhancement	Any improvement in environmental quality	Mainly direct intervention
Creation	Development of a resource that did not previously exist at the site.	Direct intervention

There are three types of river restoration: - natural recovery, enhanced recovery and direct intervention (Brookes, 1995b; 1996). Natural recovery refers to those rivers that will self-adjust or recover from disturbance without any form of human intervention. Thus, a newly straightened and over-deepened river may erode or re-deposit sediment from its bed and banks to readjust to a more stable cross-sectional form. For example, in sections of the Waren Burn, Northumbria, (UK), widened in 1949 by 30%, deposits of coarse sand had accumulated to form a bench narrowing the low flow channel to approximately the original natural width (Brookes, 1992). The process of natural recovery in straightened rivers can be encouraged by simply allowing the river space to move laterally and to recreate a more stable and meandering course, shown in the River Severn, at Llandiman in mid-Wales (Brookes, 1988). The gravel bed river was realigned during construction of a railway in the early 1850's but by 1982 had almost recovered its original slope by re-meandering in the absence of substantial bank-protection measures (Brookes, 1992). In over-wide or deep channels, deposition and silting has been observed, reducing channel capacity, for example, the River Cherwell, Oxfordshire, and the Broughton Brook, Hampshire, (Brookes, 1992). The advantage of natural recovery is that there is much less cost involved. However, this must be set against the requirements of land and time necessary for the channel to fully recover.

Natural recovery is not always possible however and occurs mainly in high-energy channels. On the basis of evidence from straightened river channels in Denmark, Brookes (1987b) found that streams recovered naturally above stream powers greater than 35 Wm^{-2} and only river channels with very high energies regain some or all of their original sinuosity. In many lowland environments, rivers have insufficient energy to erode their bed and banks and natural recovery processes alone are ineffective in restoring the channel. Similarly, in severely modified rivers natural recovery may not always be possible, as the physical constraints imposed by engineering works are too great for the channel to overcome. The nature and rate of change following works depends on available stream energy, sediment supply from upstream, or channel erosion. Deposition will occur in over-widened streams with insufficient maximum velocities, but will be limited by the available sediment, whereas erosion will be limited by the amount of available stream power. In these cases intervention is required to allow natural processes to re-establish.

The degree of intervention depends on the type of restoration required and the condition of the river channel under consideration. In some situations, natural recovery processes can be initiated by minor changes to the channel morphology or removal of engineering structures that have prevented the river from naturally adjusting. This type of intervention is referred to as enhanced recovery (Brookes and Shields, 1996) and is an intermediate strategy that ultimately relies on natural processes. An example of enhanced recovery can be found in the River Lyde, Hampshire (UK), a medium-sized chalk stream that had been artificially widened and was also over deep. The specific stream power was only 22 W m^{-2} and the low velocities had induced some sedimentation, but much of the sediment was trapped upstream of the reach and natural recovery was inevitably very slow (Brookes, 1992). The channel was narrowed to an optimum width by regrading the centre of the channel, leaving a 3-4m remnant of the existing channel as a berm at a higher level to promote deposition (Brookes, 1992). Enhancement of channels using instream flow structures to modify the flow, for example, deflectors such as those used in the Scotsgrove Brook, Oxfordshire, (UK), (Brookes, 1992) is often directed by ecological requirements as opposed to geomorphological. The use of vegetation to modify bank profiles can enhance natural channel processes that will eventually lead to river rehabilitation and restoration. Brookes (1992; 1995b; 1996) advocates the use of natural recovery where possible and where the process is negligible or slow, the installation of low-cost devices to enhance recovery. However, there are many environments where direct intervention is required to allow full restoration, involving engineering works to remove engineering structures and reconstruct the cross-sectional profile and planform.

Examples of full river restoration using direct intervention are the River Cole, Wiltshire (UK) and the River Brede, Denmark. Initial reconstruction occurs over a fixed short-term period and involves the complete redesign of the channel cross-section and planform. The channel can then readjust over longer time-spans to maintain a more naturally-adjusted state. Where complete reconstruction is required to allow full restoration of the channel, the design of the river channel is imperative to the success of the project. As the scale of river restoration schemes increases from isolated, opportunistic habitat enhancement to the multi-kilometre restoration of channel morphology there is a need for more geomorphological understanding of processes in river systems and the dynamic behaviour of river reaches within the catchment (Sear, 1994). Many geomorphological uncertainties remain in river restoration (Brookes and Shields, 1996) and when restoring a natural morphology, selecting the channel dimensions and determining the optimal size of the channel are perhaps the most difficult existing problems (Shields, 1996).

1.4 The design of channel dimensions for rivers to be restored

Methodologies for designing river channel dimensions for restoration remain unclear and there are no standard guidelines available for river managers. This is largely due to the problems of defining what a river should be restored to, site specificity and a need for further pure research to enhance knowledge of the form and process of a wide range of natural river types (Osborne et al., 1993). Before design procedures can be put in place it is necessary to establish the objectives of channel restoration.

1.4.1 What are the design objectives?

One of the main questions facing river managers concerning restoration is what are we restoring to (Tapsell, 1995; Brookes and Sear, 1996)? The restored river channel is aiming to replicate natural processes, but as Graf (1996) states in a review of geomorphology and policy for the restoration of impounded rivers in the USA, "if fluvial geomorphology has as its goal the re-creation of a pre-disturbance, natural condition, how does one define that natural condition?". In addition, it is important to consider whether reverting to a past condition is a viable geomorphological aim. With changes in catchment conditions and consequent effects on the hydro-geomorphological system, channel dimensions from a previous channel form may not be related to present and near future environmental conditions, resulting in further geomorphological problems.

The term natural is often associated with *pristine* conditions suggesting a lack of modification or a condition of purity (Brookes and Sear, 1996). Return to a pristine state therefore implies the restoration of environmental processes to a pre-disturbance condition. Defining the pre-disturbance state is dependent upon which historical context is used. Tapsell (1995) questions how far back in a river's past history it is necessary to go to define more natural conditions and how past channel dimensions should be selected. Re-creation of a semi-natural channel could be modelled on a palaeo channel from 100 or 500 years ago or a modified form created only a few decades previously. Where there is significant detailed evidence of pre-disturbance channel forms, for example, the Stensbaek stream, southern Denmark, where a series of trenches in the floodplain revealed the old channel, the approximate dimensions can be determined and used as a model for restoration design (Brookes, 1987b).

However, although geomorphological investigations allow attempts to be made to re-create historical channel forms, in practice restoration efforts are likely to be hindered by lack of knowledge of previous conditions (Brookes, 1995b). More importantly, it is impossible without past flow records to ascertain whether the dimensions of the palaeo channel will be suitable for present day flow conditions. Restoration of a pre-disturbance condition may not lead to a naturally adjusted channel in equilibrium with the current environmental controls which may have changed as a result of landuse or climatic changes which have a direct effect on the hydrologic and sediment regime. Furthermore, it may not be possible because of the scale and longevity of such environmental changes (Brookes and Sear, 1996).

1.4.2 The design of river channel dimensions for restoration schemes and environmental engineering

Where inflows and outflows of water and sediment into a reach proposed for restoration are similar to the pre-disturbance conditions and if channel properties can be deduced from historical sources or examination of channel remnants, the design can be based on the pre-disturbance condition. Where this is not the case, the design of the channel must take into account the present hydrological and environmental conditions to allow the prediction of the channel geometry that would occur without the presence of engineering works.

Design equations based on downstream hydraulic geometry can be used to predict channel dimensions for a given discharge. Ironically, their use in guiding the design of channelisation projects, has in many cases caused the problems which have made restoration necessary (Shields, 1996). However, hydraulic geometry equations particularly developed most recently for the UK by Hey and Thorne (1986), remain a recognised method for restoration design when applied to specific environments. Despite the limitations, the relationship between channel dimensions, (in particular width, and discharge) has been found to exist in many different environments (Leopold and Maddock, 1953; Bray, 1982; Hey and Thorne, 1986;) and has been used as a method for designing river channels according to the current flow conditions. More research is required to investigate the accuracy of channel dimensions predicted using channel geometry - discharge relationships for semi-natural river channels. Shields and Brookes (1996) highlighted a need for a greater understanding of the factors controlling river form and process in natural rivers to allow the improvement of restoration of natural processes.

The use of semi-natural reaches adjacent to the reach to be restored within the same river system, or in a nearby catchment with similar environmental conditions, has also been used as a method for ascertaining channel dimensions for the restored reach. Using river reaches with a similar discharge from neighbouring catchments as a model for restoration design must be treated with caution as, despite similarities in macro-scale catchment controls (for example, climate and geology), the channel may be adjusting to local factors and the structure of the drainage network. It is important to understand the factors controlling channel adjustment at the reach in the context of the downstream changes. The design of channel geometry based on reaches upstream and downstream of the reach to be restored may also be inappropriate if the reaches are unstable as a result of engineering and likely to change over short time-scales. The success of river restoration is dependent upon the stability and sensitivity of the channel and it is therefore important to assess the stability of the river to be restored before implementing design procedures.

1.5 The importance of assessing stability and sensitivity to change

Research assessing the success of river channel restoration in one of RRP demonstration sites, the River Cole (Sear *et al.*, 1998), concluded that the question of how robust geomorphological features are over longer timescales remains unanswered. To allow the stability of a restored channel to be assessed, it is important to have an understanding of the stability of the river system prior to restoration. The adjustment of river channels at a reach scale is dependent upon the catchment as a whole. Sear (1994) highlighted the significance of sediment changes throughout the fluvial system by determining the adjustment of channel morphology through erosion and deposition at a single reach. The stability of the channel and sensitivity to change over short time-scales is fundamental to restoration design. Although the importance of the catchment has been acknowledged in guiding principles for river channel design (Brookes, 1990;1995b; Sear, 1994; Kondolf, 1995; Brookes and Shields, 1996), the link between changing catchment conditions and river channel adjustment downstream in relation to the study reach needs to be strengthened. For example, Shields (1996) outlined five steps for river channel design, the first of which is to describe the physical aspects of the watershed and characterise its hydrologic response. The assessment of the catchment does not directly link with river channel adjustment and there is no consideration of stability in terms of the reach under consideration or upstream and downstream impact reaches.

In a discussion of challenges facing river management in the UK Brookes (1995a) suggested that river managers need a much clearer understanding of the factors which control and have an impact on the stability of natural river channels. The success of current design procedures is dependent upon geomorphological guidance based on an understanding of the stability of the river under consideration.

1.5.1 Geomorphological approaches to river channel design

Geomophological guidance is essential for the success of sustainable river channels (Brookes, 1995). A questionnaire was sent out at the beginning of this PhD (1995) in collaboration with two postgraduate students from the Universities of Southampton and Nottingham respectively, to investigate river restoration experiences in the UK. The questionnaires were directed at river practitioners in Environment Agency regional offices with aim of assessing the extent of river restoration in the UK and current techniques. The use of geomorphological data to be incorporated into the design of river channel dimensions was investigated using a tick box question providing six different responses and further space for comments underneath. The categories for the type of guidelines were based on existing sources of information available to the EA. The results are shown in table 1.2.

Table 1.2 **The use of geomorphological information in guiding river restoration design**

Type of geomorphological data	*Positive responses in each category (%)*
New Rivers and Wildlife Handbook	1.37
RHS data	9.8
Baseline geomorphological survey	13.7
Professional judgement	74.5
Other	0.98
No guidelines	15.7

It is clear from the results that the designs of the majority of schemes were based on professional judgement, which is dependent upon the judgement of the individual practitioner. It is unclear to what extent the judgement is based on any formal design procedures, but there is clearly little use of geomorphological guiding principles. This could be due to the directives behind restoration schemes. For example, the design of the River Cole was largely driven by consideration of reach hydraulics and requirements for ecological diversity (Sear *et al.*, 1998) as opposed to geomorphological guidance. The construction was complex and did not take into account all the points raised in a geomorphological survey (RRP, 1994).

Since the survey (Table 1.2) was completed there have been moves to begin to formalise restoration techniques and guidelines, the most comprehensive of these being a volume of guiding principles for sustainable river restoration in which many of the issues facing river managers are highlighted (Brookes and Shields, 1996). The RRP has also published a manual of restoration techniques with the first parts based methods used in the LIFE demonstration projects, the River Cole and the River Skerne.

1.6 The research problem

At present the guidelines for river channel design remain unclear and, based on evidence from 51 Environment Agency offices that have carried out restoration schemes, there appears to be little formal geomorphological input into restoration design. The use of downstream hydraulic geometry equations was found to be limited when applied with geomorphological appraisal, but the equations remain a prominent method for design of channel dimensions. Variability of the relationship between channel geometry and discharge, both between rivers and within the same river system, may be geomorphologically significant, but there is no research to date investigating what the variability represents and if it could be used to indicate river channel stability and likelihood of change. The stability of the restored reach is vital to the success of river restoration and an assessment of river channel stability and sensitivity to change should therefore be an important stage of any design process. This PhD will investigate the variability of channel - geometry discharge relations in terms of 1) the factors controlling channel form and its adjustment and 2) the extent to which residual values (representing variability in the hydraulic geometry model) are indicative of stability, both between rivers (national scale) and within the same river system (catchment scale).

1.7 Structure of the thesis

The thesis will begin by outlining the background to river channel design and downstream hydraulic geometry. The issue of stability and sensitivity to change will then be considered. The research is split into two main sections; the national study (Chapter 4) and the catchment study (Chapter 5). The national study looks at variability within downstream hydraulic geometry models and assesses the extent to which residual values are geomorphologically significant. The catchment study examines the controlling factors that may be influencing channel geometry and stability at a reach in the context of channel adjustments downstream through the catchment. The final chapter (Chapter 6) will discuss the results from both studies and attempt to draw conclusions in the form of geomorphological implications for river managers.

CHAPTER 2

THE ADJUSTMENT OF RIVER CROSS-SECTIONAL FORM

2.1 Introduction

Rivers can be considered as open systems with inputs and outputs of energy and matter (Leopold and Langbein, 1964). The inputs into the river system, namely discharge and sediment load (independent variables which integrate catchment characteristics such as soils, climate and geology), have a dominant control on the outputs from the system: the rates of mass transfer and energy expenditure, indicated by channel form. The adjustment of channel form can be considered in terms of four broad degrees of freedom: cross-sectional form; bed configuration; channel pattern; and channel bed slope (Knighton, 1998). Although each of these can be considered separately, as part of an integrated system, they should not be thought of as independent from one another.

The focus for this research is the adjustment of *cross-sectional form* and its sensitivity to change as a basis for the design of river channel dimensions in rivers to be restored. Cross-sectional form adjusts spatially and temporally to accommodate the discharge of water and sediment supplied from the drainage basin. The channel dimensions are therefore not arbitrary, but adjusted through the processes of erosion and deposition to the quantity of water moving through the cross-section so that the channel can contain most high frequency flows (Knighton,1998). In addition to these primary controls, other factors control cross-sectional adjustment at both local and catchment scales including: the composition of the channel boundary, bank stability, vegetation, sediment transport, stream power, drainage basin form and flow variability.

An understanding of the relationship between cross-sectional form (channel geometry) and these independent variables is important for river channel management and restoration of rivers and predicting the sensitivity of rivers to change. This chapter will discuss the main approaches to research on channel geometry - discharge relationships (2.2), focusing in detail on the empirical approach, encapsulated in regime theory (2.3) downstream hydraulic geometry (2.4) and channel morphometry (2.5). The influence of other controlling factors on channel geometry - discharge relationships at both local (2.6) and catchment (2.7) scales will then be considered. Finally, the variability of hydraulic geometry models will be discussed in terms of what it may represent and their use in river channel design (2.8).

2.2 Research on channel geometry - discharge relationships

Research on channel cross-sectional form has taken two main approaches, empirical and theoretical. Empirical studies of channel geometry - discharge relations were initiated by engineers working in India during the late nineteenth century, based on the discovery that the cross-sectional forms of alluvial channels adjust according to a given discharge. Regime theory, used to predict stable channel dimensions of artificial channels, was developed as a result of Anglo-Indian research at the end of the last century (Kennedy, 1895). The relationship between channel geometry and discharge in natural rivers was quantified using Hydraulic Geometry, developed by Leopold and Maddock (1953). Hydraulic geometry is divided into two main approaches: at-a-station hydraulic geometry, which deals with temporal variations in cross-sectional geometry for a range of flows up to bankfull; and downstream hydraulic geometry which investigates spatial variations in channel geometry for a specific reference discharge.

The second of these approaches (downstream hydraulic geometry) is similar to regime theory and has been used to develop design equations predicting channel geometry for a given discharge in natural channels. The variability within downstream hydraulic geometry models will be the focus for this research. To investigate the spatial variability of channel geometry within a catchment, a third empirical approach known as channel morphometry was developed during the 1970's. Morphometric analysis, otherwise known as spatial interpolation is concerned with spatial variations of channel geometry based on the relationship between cross-sectional geometry and a morphometric parameter such as drainage area or total channel length. The issue of scale is fundamental to the use of spatial interpolation which identifies changes in cross-sectional form at the reach scale in relation to the catchment.

Theoretical research, often described as rational regime theory, falls into three groups: the extremal hypotheses; tractive force theory (Lane, 1955); and subsequent work on deterministically-based models of channel geometry inspired by Parker (1978). The extremal hypotheses are based on providing relationships which predict the at-a-station equilibrium cross-sectional dimensions which the physical equations of continuity, resistance and sediment transport cannot themselves provide (Knighton 1998). Clifford (1996) states that the number of independent relations that can be used to define channel behaviour is less than the number of possible adjustments and as a result, channel adjustment is essentially indeterminate. To produce a determinate system, the extremal hypotheses incorporate an additional condition into the equations regarding the behaviour of stable rivers, often based on the assumption that the equilibrium form either maximises or minimises one of the controlling variables. The earliest work of this type was undertaken by Langbein and Leopold (1964) who developed the theory of minimum variance. This work is closely linked with empirical work on at-a-station hydraulic geometry (Leopold and Maddock, 1953) concerned with the adjustment of a specific cross-section through time. Many other hypotheses have since been developed which state that the river must satisfy a further physically based principle, for example, minimum unit stream power (Yang, 1976), minimum stream power (Chang, 1980), maximum sediment transport rate (White et al. 1982), in addition to the equations of continuity, resistance and sediment transport.

The other theoretical approach to stable channel design is Tractive Force theory (Lane, 1955) in which the equilibrium cross-section is determined subject to the condition that every particle lining the channel perimeter is at or below the threshold of motion, so that the magnitude of shear stress is large enough to prevent sediments depositing at the same time as being small enough to prevent scour. Given water discharge and bed sediment characteristics, expressions of mean velocity, slope, wetted perimeter and hydraulic radius can be deduced (Hey, 1978) based on continuity, flow resistance, and bed and bank material entrainment functions. Parker (1978) continued theoretical work on the adjustment of cross-sectional geometry based on the limitations of tractive force theory he described as the 'stable channel paradox'. His work was an explicit attempt to incorporate mechanisms of both bank erosion and deposition into the analysis of regime width using a model based on the supply, lateral diffusion and transport of sediment within the channel. Work on channel evolution models (Darby, 1994) has continued using this approach.

This research is based on variability in channel geometry - discharge relations downstream and its geomorphological significance and is therefore based on the empirical approach, as opposed to the theoretical. The following sections will therefore discuss the development of channel geometry - discharge relations based on empirical research.

2.3 Regime theory

Regime theory was initially developed through an appreciation of the principle of self-adjustment in artificial alluvial channels. For a given discharge (Q), the channel is said to be 'in regime' when a balance exists between erosion and deposition and the cross-sectional form remains stable. The relationship between the channel geometry and discharge can be expressed most simply by the form

$$y = aQ^b \tag{2.1}$$

where y is the dependent variable (for example, width or depth) predicted from the independent variable, discharge, Q. Discharge was regarded as the most important parameter controlling channel geometry and initially the influence of other factors such as boundary conditions and slope are incorporated in the coefficient a and the exponent b.

Regime equations were first quantified by Kennedy, working in India in 1895. Whilst working in the upper Bari Doab canal, he observed that there was a relationship between the non-silting velocity and maximum channel depth (equations are shown in table 2.1). Simons and Albertson (1960) point out that Kennedy's equations can only yield correct results where no scour takes place, when the right shape is selected or if dealing with very stable materials. The lack of a width equation meant that both wide shallow and narrow deep channels were wrongly deemed equally stable (Richards, 1982). Others working after Kennedy soon found that values of exponent n and constant k varied from one canal to another between the limits of 0.52 and 0.73 (Hendersons, 1966). Lindley, working around the same time, published design equations in 1919

Table 2.1: Regime equations derived for artificial alluvial channels

Author	*Equations*	*Details*
Kennedy (1895)	$V_o = kd^n$ $k = 0.84$ $n = 0.64$	Imperial units were used.
Lindley (1919)	$V_o = 0.95\ d^{0.57}$ $V_o = 0.57\ w^{0.355}$	Imperial units were used.
Lacey (1929, 1933)	$V = 1.15\sqrt{(fR)}$ $P = 2.67\ Q^{0.5}$ $S = 0.00039 f^{2/3} / Q^{1/9}$	f is a silt factor dependent on the diameter (mm) of the predominant type of sediment transported.
Blench (1950)	$w = \frac{Fb^{0.5}}{Fs^{0.5}} Q^{0.5}$ $d = \left[\frac{F_s}{F_b}\right]^{1/3} Q^{0.33}$ $S = \frac{Fb^{5/6} Fs^{1/12} x^{1/4}}{3.63 g\ Q^{1/6}}$	F_b : Bed factor F_s : Side factor 0.004 - loam of very slight cohesiveness 0.018 - loam of medium cohesiveness 0.027 - loam of high cohesiveness
Simons and Albertson (1960)	$w = 0.9\ k_1 Q^{0.5}$ $d_1 = 1.21\ k_2\ Q^{0.36}$ $d_2 = 2.0 + 0.93\ k_2\ Q^{0.36}$ $S = 0.0000028$ to $0.71\ Q^{0.431}$	d_1 for $R < 7ft$ d_2 for $R > 7ft$ K_1 K_2 1)Sand bed and banks 3.5 0.52 2)Sand bed and cohesive banks 2.6 0.44 3)Cohesive bed and banks 2.2 0.37 4)Coarse non-cohesive material 1.8 0.23 5)Sand channels with heavy load 1.7 0.34
Mahmood et al (1979)	$w = 4.93\ Qb^{0.51}$ $d = 0.53\ Qb^{0.31}$	

derived from data obtained from the Lower Chenab Canal. Lindley recognised the need for three independent relations to characterise the three assumed degrees of freedom so that this was the first time that average bed width and depth were used as regime variables. The width and depth are a function of the non-silting velocity allowing a width-depth relationship to be derived (Richards, 1982). Lindley's equations, although not popular in the United States, were used extensively elsewhere, until about 1935.

The development of modern regime theory is based on the work of Lacey (1929). He developed formulae based on a reanalysis of all the systematised data collected relative to stable channels in which the discharge was reasonably constant (Nixon, 1959). In producing a complete set of design equations Lacey removed the difficulty of varying exponents found in Kennedy's equations (Henderson, 1966). Lacey's first equation was based on the observation that if V was correlated with R (hydraulic radius) instead of y (maximum vertical depth), the exponent of R was found to be close to 0.54 for all the data set used up to that time (Henderson, 1966). The variation from one canal system to another, appeared to depend on the type of silt in the canal leading to the development of a silt factor, *f*. This was the first time a sedimentological constraint was explicitly introduced into design equations, any constraints imposed by sediment and boundary conditions previously being hidden in the coefficients and exponents. Until this point, there had been no need to explicitly define them due to the similar conditions found at both Kennedy's and Lindley's sites. The regime equations developed by Lacey have been variously modified since their introduction and are most commonly expressed in a form derived by Inglis (1949), cited in Richards (1982) shown in table 2.1, which is the most useful for design procedures. The introduction of a sedimentological factor, opened up the opportunity for future development of equations with a wider applicability.

Blench, working in the 1950's, explored the influence of sediment source and transport postulating that channel geometry in practice must be dependent not only upon the sediment in transport and bed composition, but also materials composing the bank. He introduced a bed factor F_b and a side factor F_s allowing for varying degrees of channel boundary cohesion (Blench, 1969). These were initially defined as

$$F_b = v^2/d \tag{2.2}$$

$$F_s = v^3/w \tag{2.3}$$

In this case, it appears that the bed factor is essentially the Froude number and the side factor is a measure of the hydraulically smooth bank (Blench, 1969). Any improvement of design equations using the side factor (2.2) is largely a ratio correlation effect because of the inclusion of channel width (w) (Benson, 1959). The bed factor can also be defined in terms of grain size (D_{50}) and bedload concentration and limiting values of the side factor have been specified for different bank materials (table 2.1) (Richards,1982).

Research continuing the idea of widening the applicability of regime equations by using explicit representations of varying boundary conditions in quantifiable values, was carried out by Simons and Albertson (1960). They set out to investigate the validity and applicability of regime theories developed in India, to canals in the USA with the overall aim of relating regime theory to the tractive force method of stable channel design. The type of bed and bank material was found to be an important influence on the wetted perimeter, highlighting the importance of boundary conditions as an independent variable and leading them to conclude that the regime theories could only be applied under a limited range of conditions. To expand the applicability of the equations, five classifications of channel types represented by varying constants k_1 and k_2 were developed based on different boundary conditions, a simpler method than that employed by Blench (1969).

The regime equations described so far have been derived for canals and straight alluvial channels. Attempts to apply regime theory to natural river channels by treating rivers as fluctuating canals, have been limited by the fact that rivers are complex systems with variable discharge and sediment loads, developed on different boundary materials. Hydraulic geometry developed to provide a method of quantifying the relationship between channel geometry and discharge in natural rivers.

2.4 Hydraulic Geometry

Leopold and Maddock's (1953) paper on 'The Hydraulic Geometry of Stream Channels and some Physiographic implications' was the first work to quantify the relationship between channel geometry and discharge in natural rivers and has been the catalyst for a great deal of field research over the past four decades (Park, 1995). As part of the post war paradigm shift towards a more quantitative approach to geomorphology, the research formulated the basic approach to hydraulic geometry which assumes that discharge (Q) is the dominant independent variable and that dependent variables are related to it through simple power functions:

$$w = aQ^b \quad (2.4)$$
$$d = cQ^f \quad (2.5)$$
$$v = kQ^m \quad (2.6)$$

Leopold and Maddock (1953) used hydraulic geometry to consider two fundamentally different problems; *'at-a-station'* hydraulic geometry, the quantitative description of variations in stream width, depth and velocity, and related factors with changing discharge over time (Phillips, 1990) and *'downstream'* hydraulic geometry, the approach considered in this research, which deals with the variations in bankfull geometry along and between streams at comparable discharge frequencies.

Research on downstream hydraulic geometry has been carried out according to two research objectives (Richards, 1982). The first considers the downstream changes of flow geometry within the varying overall cross-section and at a constant flow frequency so that between section comparisons can be made of width, depth and velocity; the second represents the geomorphological analogue of 'regime theory', developing equations for the prediction of stable channel dimensions from a given discharge. Implicit in both forms of analysis is the requirement to relate geometric properties to a single characteristic discharge (Wharton, 1995). Although rivers experience continuously variable discharge, it has been argued that a dominant or channel forming discharge can be specified (Inglis,1947; Nixon, 1959) which typifies the range of competent discharges and controls channel morphology (Ackers and Charlton, 1970).

2.4.1 Dominant discharge

Dominant discharge has been defined in several ways and there is still debate over which is the channel forming discharge (Knighton, 1998, p.163). Dominant discharge has been defined as the flow which determines particular channel parameters, such as cross-sectional capacity (Wolman and Leopold, 1957) and meander wavelength (Ackers and Charlton, 1970); or the flow which performs the most work, where work is defined in terms of sediment transport (Wolman and Miller, 1960, see figure 2.1). The flow which just fills the section of an alluvial channel without overtopping, known as the bankfull flow (Q_b) has often been equated with the formative or dominant discharge, based on an approximate correspondence between the frequency of bankfull discharge

(Wolman and Leopold, 1957) and the frequency of that flow which cumulatively transports most sediment (Wolman and Miller, 1960).

Bankfull discharge is usually estimated indirectly by identifying the bankfull stage and applying a stage-discharge relationship (Richards, 1982, p.136). However, there are no consistent methods for defining the bankfull channel, although many have been devised (see table 2.2).

Table 2.2 Definitions of bankfull based on Williams (1978), Wharton (1989)

Definition	*Authors*
Morphometric	
• The height of the lower limit of perennial vegetation	Schumm. (1960); Sigafoos. (1964); Speight. (1965); Nunally (1967); Bray (1975)
• Well-defined lichen limit marking maximum stages which recent peak discharges have attained.	Gregory (1976)
• Indicator Species to confirm landform identification - channel shelf, terrace	Hupp (1986)
• The elevation of the upper limit of sand-sized particles in the boundary sediment.	Nunally (1967); Leopold and Skikitzke (1967).
• The elevation at which the width -depth ratio of the cross-section becomes a minimum	Wolman (1955); Harvey (1969); Pickup and Warner (1976)
• The stage corresponding to the first maximum of the bench index	Riley (1972)
• The stage corresponding to a change in the relation of cross-sectional area to top	Williams (1978)
Sedimentary	
• The height of the valley flat	Nixon (1959); Woodyer (1968); Kellerhals, Neil and Bray (1972); Dury (1973)
• The elevation of the most prominent bench	Kilpatrick and Barnes (1964)
• The elevation of the active floodplain	Wolman and Leopold (1957); Leopold and Skibitzke (1967); Emmett (1972, 1975)
• The active-floodplain level	Hedman et al (1974); Osterkamp W.R and Hedman (1982), Wharton (1989)
• The elevation of the low bench	Schumm (1960); Bray (1972)
• The elevation of the middle bench	Woodyer (1968)
• The average elevation of the highest surfaces of the channel bars	Wolman and Leopold (1957); Hicken (1968); Lewis and McDonald (1973)

Williams (1978) reviewed the concept of bankfull discharge and the methods used to define the bankfull level. Most of the sedimentary definitions are based on the interaction between the river, floodplain and terrace systems. Williams (1978) concluded that the active floodplain level, hereafter referred to as the *bankfull level*, is the most significant level as far as the river's current situation is concerned. The bankfull level was described by Williams (1978) as "an overflow surface that is periodically constructed and eroded by the river, but undergoing net change during the 'present' time (past 10 years)". Where no active floodplain is identifiable at the reach (one of the main disadvantages of the active flood level), morphometric measures such as perennial vegetation, breaks in slope or the grain size boundary can be used to identify the active bankfull level. A combination of factors is often used to accurately identify the bankfull level including the level at which the width:depth ratio is at a minimum used by Wolman, (1955), Harvey (1969) and Pickup and Warner, (1976).

The frequency of bankfull discharge has been the subject of much debate. Early research by Wolman and Leopold (1957) suggested a common return period (T_p) for bankfull discharge of 1-2 years, which fostered the assumption that cross-sections adjust to accommodate a uniform bankfull frequency with an average return period imposed by the annual hydrological cycle (Richards, 1982). Dury (1973) demonstrated the similarity between Q_b and discharge with a return period of 1.58 years ($Q_{1.58}$) for a dataset of American rivers. However, other research has shown that bankfull discharge is not necessarily of a frequent occurrence, even within the same river basin (Pickup and Warner, 1976). Hey (1975) showed that bankfull discharge in the rivers Tweed and Severn (England) could be equated with $Q_{1.5}$ downstream, but in the River Wye were characterised by bankfull discharge with a T_p of less than $Q_{1.5}$ in the upper reaches and more than $Q_{1.5}$ in the lower reaches. Pickup and Warner (1976) undertaking research in the Cumberland basin (Eastern New South Wales, Australia) found that the frequency of bankfull discharge fell into two distinct groups, those less than 10 years and those greater than 20 years, accounted for by differences in the degree of incision.

Catchment characteristics have also been found to have an effect on bankfull frequency, for example, Petit and Paquet (1997) found that the bed material related to channel size and basin are also important in terms of the frequency of Q_b which was found to have a low T_p for rivers of about 0.5 years in the case of small pebble bed streams on impermeable strata but longer T_p of 1.5 years for larger rivers of this kind. Rivers with baseflow dominant regimes were confirmed to have a high recurrence interval always exceeding two years and often much more. Furthermore, rivers with pebble beds developed on a soft substratum have a larger bed capacity before overflowing and consequently a higher bankfull recurrence interval (Petit and Paquet, 1997).

The strongest basis for the use of bankfull discharge originally was its close correspondence with the most effective discharge (Q_{me}), the flow which cumulatively performs the most work where work is defined in terms of sediment transport. There is still debate over which flow events are the most effective. For example, Baker (1977) has argued that rarer flows are more effective agents in streams with a high proportion of large discharges and relatively resistant boundaries. However, Pickup and Warner (1976) found that bankfull was at least ten times the size of the most effective discharge, recurring on average about 3-5 times a year.

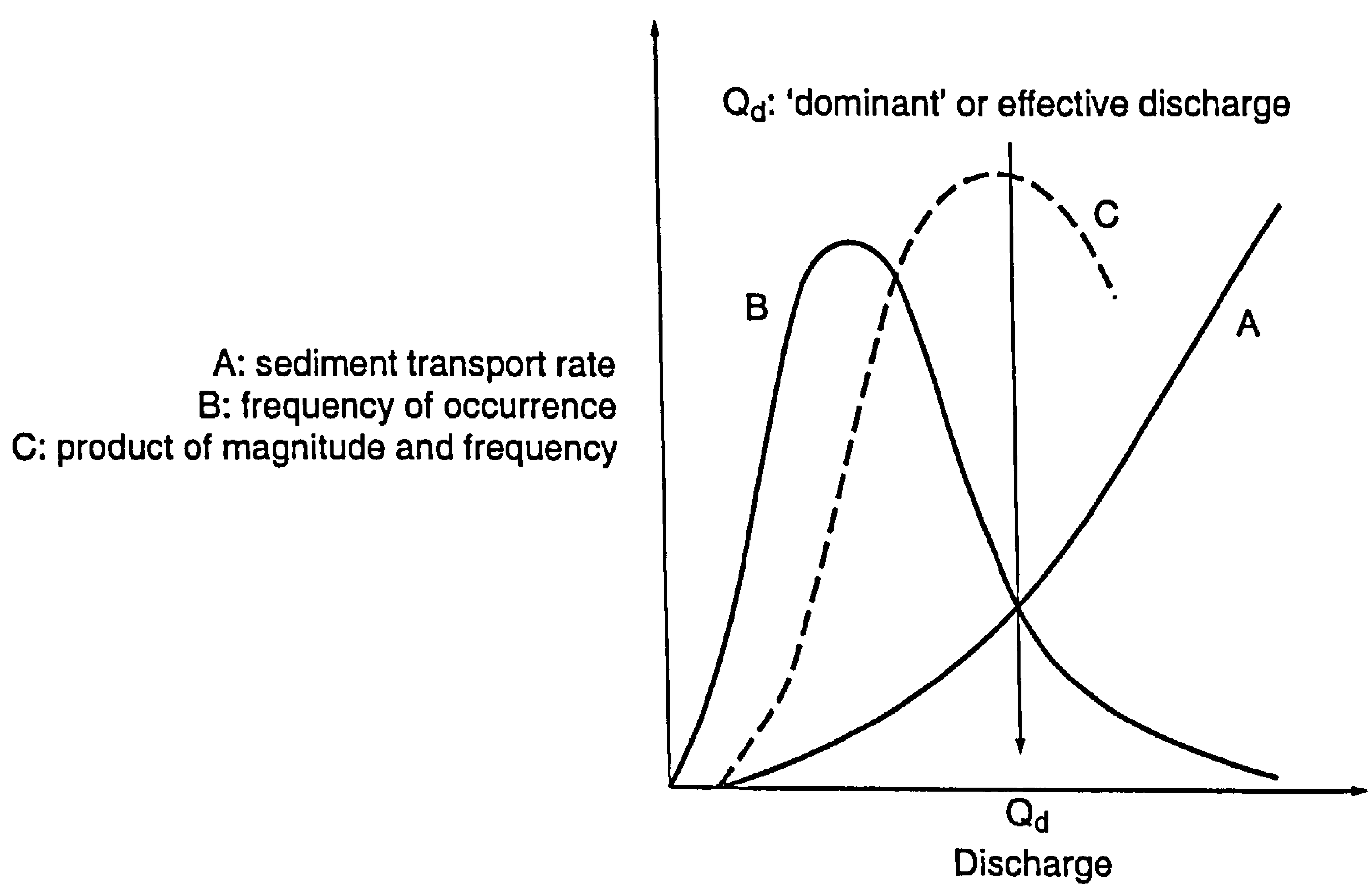


Figure 2.1 The concept of magnitude and frequency (Wolman and Miller, 1960)

The most effective discharge in terms of sediment transport is based on the concept of magnitude and frequency developed by Wolman and Miller (1960) illustrated in figure 2.1. The concept is based on the premise that although extreme discharges can individually transport large volumes of sediment, they are so infrequent that the smaller more frequent floods are responsible for transporting most sediment over the long term. Since the work by Wolman and Miller (1960) it has been found that bankfull discharge may not always be the most effective flow in terms of sediment transport. In their original derivation Wolman and Miller (1960) considered suspended load, but it is bed load which is the most relevant in terms of channel adjustment (Knighton, 1998, p.164). The overall shape of the effectiveness curve (fig 2.1) is determined by the transport rate function which is dependent on the calibre and type of load and the discharge frequency distribution which varies downstream and from catchment to catchment.

Measurement of the most effective flow is based on the relationship between sediment transport and discharge. For example, Pickup and Warner (1976) determined Q_{me} by dividing the flow into small classes, finding the duration of flow within each class, calculating the mean bedload discharge within each class and multiplying it by the duration. From a histogram showing the bed-load regime, the most effective discharge can be identified as the mid-point of the class that transports the most bed-load. The discharge cumulatively transporting most material, was also used in research on the Brahmaputra river (Thorne *et al.* 1993) and the Lower Mississippi (Biedenharn and Thorne, 1994) where the dominant discharge corresponds to bar-full stage, the height to which mid channel bars grow through accretion. However, it is often difficult to measure sediment discharge correlated with the flow regime as sediment discharge is seldom routinely measured at gauging stations in the UK (Hey and Thorne, 1986). This has meant that other less absolute definitions of dominant discharge have been more widely used, based only on flow records. Many different recurrence intervals have been selected for use as the dominant discharge; for example, mean annual flood (Q_{maf}) (Leopold and Maddock, 1953) or the 1.5 year flood ($Q_{1.5}$) (Bray, 1982) which was based on statistical correlations to select the discharge which resulted in the highest coefficient of determination and lowest standard error when computing the simple hydraulic relationships of Leopold and Maddock (1953).

The variability in recurrence intervals for Q_b and Q_{me} and the extent to which bankfull discharge and most effective flood correspond are inherent problems of the dominant discharge concept. Fundamentally, no single discharge frequency is equally important as 'channel forming' at all positions (Richards, 1977). In rivers or segments of rivers where the flow regime is very variable or the channel boundary is very resistant, high magnitude, low frequency floods may control channel form, so that the concept of dominant discharge becomes less relevant (Baker, 1977). This is often the case in semi - arid rivers (Graf, 1988), but in many perennial, especially humid temperate rivers, the use of a dominant discharge is more acceptable and has facilitated many studies of channel geometry discharge relations which have been used for channel design. It is crucial to recognise, however, that channel form is the product of a range of flows and flow recurrence intervals vary both within and between river basins. The limitations of using a single representative discharge must be recognised in any studies of channel geometry - discharge relationships in natural rivers.

2.4.2 A review of research on downstream hydraulic geometry

Following Leopold and Maddock (1953) other authors continued the quantitative study of downstream hydraulic geometry (equations shown in table 2.3) using various definitions of dominant discharge. Nixon (1959) formulated his channel geometry - discharge equations using bankfull discharge as the dominant discharge which might be expected to occur with equal frequencies on different rivers. Bankfull discharge was plotted against flow frequency for 22 British rivers and, although considerable scatter was observed in the plot, Nixon arrived at an average flow frequency of 0.6% for bankfull discharge. This was fundamental to the application of the relationships to design problems. The procedure first involved the preparation of a flow duration curve of the channel concerned. The value of the discharge was then read off the curve at the frequency of 0.6% and the value entered into a set of channel geometry equations which were derived from the British dataset.

Kellerhals (1967) designed regime-type formulae for relating the stable dimensions and slopes of gravel bed channels to discharge and bed material size by analysing field data collected from seven selected reaches, data on canals and rivers previously reported and laboratory studies. He based his equations on two basic assumptions as follows: that a formative or dominant discharge can be defined for the channels under study and that the bedload transport rates are negligible at this discharge. For the river data, dominant discharge was selected according to the location of the reach. For reaches close to lake outlets an extreme flood of low frequency was selected because bed and bank erosion caused by such a flood cannot be repaired. On reaches

Table 2.3 : **Hydraulic-geometry equations derived for natural river channels**

Authors	*Equations*	*Details*
Leopold and Maddock (1953)	$w = {*}Q_{maf}^{0.50}$ $d = {*}Q_{maf}^{0.40}$	*The coefficients vary for each system.
Nixon (1959)	$w = 1.65\ Q_b^{0.5}$ $d = 0.545\ Q_b^{0.33}$	Bankfull determined by 0.6% frequency.
Kellerhals (1967)	$w = 1.8\ Q_d^{0.5}$ $d = 0.166\ Q_d^{0.166}\ D_{90}^{0.12}$ $s = 0.120\ Q_d^{-0.40}\ D_{90}^{0.92}$	
Charlton et al. (1978)	a) $w_b = 3.74\ Q_b^{0.45}$ $d_e = 0.066\ D_{65}\ S^{-1}$ b) $w_b = 2.43\ Q_b^{0.41}\ S^{-0.098}$ $d_e = 0.24\ Q_b^{0.30}\ D_{90}^{0.24}\ S^{-0.20}$	a) channels with negligible sediment load b) channels with appreciable sediment load
Bray (1982)	$w = 2.38\ Q_2^{0.527}$ $d = 0.266\ Q_2^{0.333}$ $s = 0.0354\ Q_2^{-0.0354}$	
Hey (1982)	$P = 2.20\ Q^{0.54}\ Q_s^{-0.05}$ $R = 0.161\ Q^{0.41}\ D_{50}^{-0.15}$ $d_m = 0.252\ Q^{0.38} D_{50}^{-0.16}$ $S = 0.679\ Q^{-0.53}\ Q_s^{0.13}\ D_{50}^{0.97}$	
Hey and Thorne (1986)	$w = 4.33\ Q_b^{0.5}$ $w = 3.33\ Q_b^{0.5}$ $w = 2.73\ Q_b^{0.5}$ $w = 2.34\ Q_b^{0.5}$ $d = 0.22\ Q_b^{0.37}\ D_{50}^{-0.11}$ $S = 0.087\ Q_b^{-0.43}\ D_{50}^{-0.09} D_{84}^{0.84} Q_s^{0.10}$ $p = S_v / S$	[Veg I] [Veg II] [Veg III] [Veg IV] [Veg I-IV] [Veg I-IV] [Veg I-IV]
Reeves (1994)	$w = 3.42\ Q_{maf}^{0.39}$ $d = 0.59\ Q_{maf}^{0.16}$	Based on bankfull river sites used by Wharton (1989)

elsewhere in the catchment, flood discharges with recurrence intervals of 3-5 years were considered representative. Wherever feasible, the highest discharge during which measurements were made, was taken as dominant discharge, a different definition of dominant discharge than is generally used (Kellerhals, 1967). As the flood frequency curves of the rivers under study are flat, the range of reasonable dominant discharge values is small. Kellerhals (1967) derived four equations for gravel channels based in a "low transport equilibrium". It is interesting to note similarities with Leopold and Maddock's (1953) Q exponents found in equations based on discharges of fixed frequency.

Charlton *et al.* (1978) looked at the hydraulic geometry of 23 gravel bed rivers in Britain. For practical purposes, they highlighted the need to obtain a single value of discharge which relates to the hydraulic geometry of the channel. Dominant discharge was defined as bankfull discharge on the basis that at this flow most of the sediment which very rarely moves in gravel rivers may be in transport. Charlton *et al.* (1978) used a plot of Shields' transport parameter for the 10, 50 and 90 percentile bed material sizes. In a few rivers at bankfull flow, grain size D_{90} is at the threshold of motion but below for most. When the dominant discharge flows down a channel it would be expected that most, if not all, of the sizes of bed material would be in motion. This therefore suggests the dominant discharge could be defined as that flow at which a selected bed material size is at the threshold of motion. Thus, dominant discharge could be derived knowing the width, slope, and selected grain size. Charlton *et al.* (1978) use the term bankfull discharge so that it is not assumed to be the dominant discharge of other authors.

Until the 1980's the regime equations for the design of natural rivers focused on straight alluvial channels. Bray (1982), Hey (1982) and Hey and Thorne (1986) extended the range of applicability of regime equations to the design of meandering mobile-bed rivers with a riffle-pool bed topography. They recognised the need to develop equations that can be used to determine the plan shape of a river for design purposes and which explicitly define the effects of sediment load on the hydraulic geometry of the channels.

Bray (1975, 1982) developed regime equations for gravel bed rivers from a data set of 70 gravel bed rivers in Alberta, Canada. Equations for width, depth and velocity were developed as power functions of the two year flood flow and characteristic bed material size. The generalised hydraulic geometry exponents ($b = 0.527$, $f = 0.333$ and $m = -0.140$) for the downstream analysis of the Alberta gravel bed data are close to the modal class of values for b, f, and m reported by Park (1977). The values of b, f and m plot at the centre of the grouping on a triaxial graph of humid temperature climates. They also agree with Leopold and Maddock (1953) suggesting some consistency in the rates of width and depth adjustment. Bray (1982) tested four methods for calculating channel dimensions and found that the best-fit relationships for width, depth and velocity for the same discharge and bed material size were of the same statistical significance as the equivalent hydraulic geometry type relationships.

Hey (1982) and Hey and Thorne's (1986) work has concentrated on gravel bed rivers. Hey (1982) used bankfull discharge data from three UK rivers from both gauged reaches and also by derivation from the channel dimensions and sedimentological conditions. The derivation was based on the Colebrooke-White equation together with the Darcy-Wiesbach equations. Hey (1982) used three approaches for evaluating dominant discharge: first, using natural bankfull discharge and associated sediment transport rates at neighbouring stable sections; secondly, from the flow transporting most sediment; and thirdly, from the 1.5 year flood of the annual maximum series. Hey reasoned that, for stable gravel bed rivers in the UK, hydraulic conditions limit sediment transport rates and there is virtually no difference in flow regime, therefore bankfull discharge would not be expected to vary much between sites. Whilst acknowledging Nixon's (1959) work, but appreciating the considerable scatter on the plot of bankfull discharge against flow frequency, it was proposed that the frequency of bankfull conditions may correlate. This was tested and it was found that for gravel bed rivers in the UK, the 1.5 year flood on the annual series can be used as the dominant discharge for design purposes.

Data from 62 river sites across the UK were collected and used by Hey and Thorne (1986) to derive equations by multiple linear regression procedures to predict bankfull channel dimensions from a number of independent variables, including bankfull discharge to estimate a measure of bedload transport, bed material size and variability, bank shear strength, vegetation density and valley slope. They found that the computed width equation did not support Bray's (1982) equation possibly because of the inclusion of median bed material size (D_{50}). The equation did relate to those equations based on discharge alone indicating that neither D_{50} nor D_{84} affected channel width (Hey and Thorne, 1986). Bank vegetation proved to have a major control on width as well as wetted perimeter and mean flow velocity thus resulting in the inclusion of vegetation type into the analysis to produce a set of practical design equations. The exponents were found to be in close agreement with Nixon (1959), Kellerhals (1967), Simons and Albertson (1960) and Charlton (1978). The exponents in the depth equations were found to depend upon the bedload transport rate, which compare well with Nixon's equation (1959). Hey and Thorne (1986) also used the data to produce equations for dimensions of riffles and pools and to confirm existing equations for sinuosity and meander arc length.

The limitations of hydraulic geometry equations have largely been determined by the constraints imposed by geotechnical conditions; for example, most of Hey and Thorne's (1986) work has been focused on gravel bed rivers. To ensure a more general applicability it is necessary to obtain field data from a wide range of environments, to maximise the variance within and between variables.

Reeves (1994) attempted to increase the range of conditions covered by regime equations in the UK by developing a set of geometry relations based on a data set established by Wharton (1989) to produce channel-geometry equations for the estimation of flood discharge. The data set was sub-divided and provided channel-form discharge relations based on the height of the active bankfull level and the level of overtopping which may be higher than bankfull in incised channels. Again the highest correlations were associated with the width expressions. This corresponds with conclusions of previous researchers who have found it most appropriate to represent width as independent of sedimentological factors. The exponent of the overtopping equation derived for the width equation of 0.49 is close to the widely attained value of 0.5 that is now accepted as the norm. The values of the regression constants fall within the range of those for previously developed equations (reported in Wharton, 1995). The low R^2 values for depth relations developed by Reeves (1994) confirm that depth is poorly represented exclusively as a function of discharge.

2.4.3 Discussion of the downstream hydraulic geometry concept

Since the publication of Leopold and Maddock's (1953) paper there has been much discussion of the concept of hydraulic geometry and its limitations, many of which were recognised by the authors (Clifford, 1996). One of the main problems is the use of dominant discharge. As discussed in section 2.4.1, the selection of a dominant discharge related to bankfull is difficult and the return periods for bankfull discharge may differ both between rivers (Hey, 1975) and within the catchment. No single discharge is equally important in channel formation at all positions downstream (Richards, 1977). The selected flow frequency may be competent at some sections but not at others and is therefore of variable significance, which can result in discontinuous trends if flow geometry is related to a constant flow frequency. Thornes (1970) found that it was necessary to fit two separate regression lines for different reaches of the Xingua-Araguaia catchment, Amazon, due to differences in the relationship between width and discharge in the headwaters and the main channel. Dominant discharge is a simple measure of average flow magnitude and does represent the variability of the flow regime which has an important influence on channel form adjustment (Harvey, 1969; Pickup and Reiger, 1979; Yu and Wolman, 1987).

However, despite the problems and the generalisations inherent in dominant discharge, the findings from research documented in section 2.2.3 have shown consistently strong and statistically significant associations between a dominant discharge and river channel dimensions. Darby (1994) highlighted the significance of dominant discharge as a control on channel form by undertaking a sensitivity analysis of the variables controlling channel width for the development of a model predicting channel adjustment through time (Osman and Thorne, 1988). Sensitivity analyses were carried out to establish the relative importance of individual variables in controlling channel adjustment. The magnitude of change was considered, but also the rate of change and length of time it takes for a stable channel width to be attained following the onset of widening. He found that the single most dominant variable controlling overall change in channel width and depth in these simulations was discharge. Darby (1994) states that :

"The result [of the sensitivity analysis] is consistent with the traditional use of bivariate relationships in hydraulic-geometry analysis, in which channel morphology variables are related to 'channel forming' discharge alone. It appears from the results of the sensitivity tests conducted here that, insofar as discharge is the dominant variable, the use of such bivariate relationships is justified." p.203

The sensitivity parameters for width and depth for discharge were at least an order of magnitude larger than the next most influential variables relating to bank characteristics confirming that discharge is the most dominant variable in terms of its influence on width and depth. This supports the argument of Bettess and White (1987) that

"The very success of regime theories in predicting channel width when such theories have in the past completely ignored both the composition of the banks and the method of bank erosion, must suggest that such factors are only secondary [to discharge] in the determination of width." p.787

The use of dominant discharge has facilitated the generation of a large number of channel geometry discharge relationships in the UK (Wharton, 1995) and similarities between a wide range of rivers in different physiographic settings do suggest a common tendency for channels to adjust to conditions of imposed discharge and sediment load (Clifford, 1996).

Another limitation of hydraulic geometry is that empirical equations are only applicable over the range of conditions for which they were derived. For example, Charlton (1975) has shown that regime equations developed by Lacey and others can only be applied to straight channels where sediment transport rates are low, width:depth ratios are >5 and relative roughness lies between 3 and 80. It is therefore essential that empirical relationships are applied in the context of the data from which they were derived.

Finally, the multivariate nature of controls on river channel geometry must be considered. Downstream, the effects of catchment characteristics on hydraulic geometry at both catchment and local scales must be examined in addition to changes in discharge. Different independent variables may have varying effects according to the river channel type and at different points along the river system. The downstream variability of channel - geometry discharge relationships is therefore important and is considered below in section 2.5, the channel morphometry approach.

2.5 The channel morphometry approach

A third major approach towards understanding cross-sectional change throughout a river system is the channel morphometry approach. Park (1995) argued that whilst hydraulic geometry studies reveal much about the internal adjustment of channel form and size related to changing discharge, they reveal little about spatial variations or interrelationships between channel form and possible environmental controls. Networks and channels have traditionally been studied separately (Knighton, 1998, p.58) and channel morphometry has evolved to overcome this problem, relating measures of drainage basin form to changes in channel morphology. Although there has been progress in this field, particularly during the 1970's, it remains incomplete and is therefore an area of research with great potential for development and application.

2.5.1 The concept of channel morphometry

Channel morphometry is based on the principle of allometric growth (Huxley, 1924), which states that the relative change of part of a system is a constant fraction of the relative change of the whole system or some part of it (Ebisemiju, 1991). The quantification of relationships between parts of the system are based on power laws (known in biology as 'equations of simple allometry' (Gould, 1966)), similar to those used by Leopold and Maddock (1953) to develop hydraulic geometry relationships. Park (1978) highlighted the variability in the exponents of hydraulic geometry relationships from wide range of rivers channels (Park, 1977; Rhodes, 1977) and suggested that discharge may not be suitable for identifying *regional* spatial patterns of channel morphology. Woldenberg (1969) proposed that downstream channel geometry downstream is related to areal geometric progressions and on the basis of this Park (1978) argues that spatial variations in channel geometry should be based on the conventional allometric use of power law relationships. Power laws seek to relate the size of parts of the system (channel size and form) to the whole system (a measure of spatial and scale location of the reach within the channel network or drainage basin).

2.5.2 Morphometric parameters and network analysis

Drainage network analysis, used to gain an understanding of the evolution and structure of river networks and the relationship between the drainage basin form and the hydrological system, is based on two related concepts *stream order* and *drainage density* (Horton, 1945) which describe drainage network composition. Stream ordering, developed by Horton (1945) and modified by Strahler (1952, is based on the classification of river segments according to their position within the network, with increasing magnitude from the headwater tributaries downstream to the source of the main channel. The main limitation is that discharge can change when a lower order tributary enters a higher order stream, but the order of the stream remains the same, highlighting the problem of using an ordinal ordering system. Other more detailed indices related to the density, size and internal structure of the drainage basin have therefore been used in morphometric studies.

Drainage density (Dd) is the channel length per unit area, calculated by dividing the total channel length (TCL) by the catchment area (Ad). Catchment area is highly correlated with discharge (for example, Emmett, 1975) and was found in the Flood Studies Report (1975) to be the most important parameter for predicting Q_{maf}. Morphometric studies have often adopted catchment area as a surrogate for discharge (Gregory and Walling, 1973; Park, 1975) under the assumption that the rate of runoff is uniform over the catchment and that a linear relationship exists between the increase in drainage area and increase in bankfull discharge downstream. However, Petts (1979) argues that the attenuation of flood peaks due to channel storage and the spatial variation in the rate at which peak discharges increase downstream will tend to reduce the rate at which peak discharges increase downstream and the assumed linear relationship may therefore not be valid. This view was supported by Knighton (1987a). Although the relationship between catchment area and bankfull channel capacity was relatively strong ($R = 0.81$) when tested on rivers in the Derwent catchment, UK, (Petts, 1979) the rate of runoff was found to vary markedly between the limestone and sandstone-slate areas and there was also difficulty in determining drainage divides. On the basis of this and evidence that total channel length (TCL) showed a stronger relationship with bankfull channel capacity ($R = 0.94$) than catchment area, Petts (1979) suggested that TCL may be a more useful surrogate measure of discharge for use in morphometric studies. Brookes (1987a) also used TCL as opposed to drainage area because of the difficulty of determining accurate values for A_d from maps for closely spaced downstream sections. In morphometric studies focusing on downstream changes network magnitude can be superior to drainage area in predicting Q_{maf}, especially in large basins where the precise delineation of the drainage network is less critical (Knighton, 1987b, 1998, p.61).

Total channel length is generally derived from the blue-line network from maps of consistent scale (1:25000 in the UK). It is important to ensure consistency of measurement and that the scale of maps is consistent throughout. The main difficulty associated with using stream length is the definition of the headward limits of tributaries, a problem complicated by short-term fluctuations in stream head position and the differences between perennial, intermittent and ephemeral streams (Knighton, 1998). Contour crenalation can be used to extend the network but reliability can be variable and consistency of measurement must again be stressed in order to minimise further error.

2.5.3 The use of channel morphometry

The approach was prompted as a method of identifying and quantifying human-induced changes to river channels, either by comparison of adjacent streams (one natural and one modified) or comparison along an individual stream, where the upper portion is in a natural state and the lower portion has been modified. An early example of this was the investigation of the adjustment of channel capacity of the River Tone downstream from Clatworthy reservoir, Somerset, UK (Gregory and Park, 1974). It was proposed that there could be two possible forms of adjustment, depending on the effect of the reservoir on downstream peak discharges. Where floodwaters are released as surges, the possibility of downstream peak discharges of increased magnitude but decreased frequency could lead to the increase of channel capacity. Alternatively, where the floodwaters are impounded a decrease in channel capacity would be expected. The method used the relationship between river channel capacity and drainage area downstream through the catchment, to establish the magnitude of channel adjustment. In this type of analysis the morphometric parameter is used as a surrogate for discharge.

Gregory and Park (1974) tested the validity of using drainage area instead of discharge, by plotting logarithmic values of low flow discharge and catchment area and found that the relationship was significant at the 99.9% significance level. Using the method they were able to determine the actual change in channel capacity and the extent to which the effect of adjustment persisted along the channel. It was found that the effect of the reservoir extended for at least for at least 11km downstream until the catchment area contributing to the Tone was at least four times that of the area draining to the reservoir. Park (1977) used the morphometric approach to relate various geometric parameters to drainage area to indicate morphometric changes and the nature and direction of those changes. The b exponents were found to reveal most about allometric changes. Bankfull channel capacity clearly increases with increasing drainage area and since the two variables are dimensionally balanced, the b value of 0.49 indicates a state of negative allometry (the ratio of channel capacity to drainage area decreases as drainage area increases (Park, 1977)).

The major advantage of the spatial interpolation approach is the evaluation of river channel processes and the magnitude of adjustment to prevailing environmental conditions where there are no available flow records. Ebisemiju (1991) used geomorphic and morphometric parameters of channel perimeter cohesion and discharge to look at variation throughout the River Elemi catchment, Nigeria. Multivariate regression analyses showed that different controls were dominant at different spatial locations throughout the catchment with 91% of cross-sectional variance being explained by discharge measures in the upper head water areas but 75% of variance explained by perimeter cohesion index in the lower reaches. The fact that a single power function cannot adequately describe the relationships between channel size parameters and discharge has been recognised in hydraulic-geometry studies and was re-affirmed by Ebisemiju who identified three equations for different segments of channel.

Channel morphometry provides a valuable framework within which to consider spatial variations in channel form properties. These can be evaluated at a wide variety of scales from channel variations along portions of individual streams and tributaries within a stream network, to those between streams in a specific region, to variations at the global scale. The development of channel morphometry has strengthened the search for explanations of unexplained variability. The identification of factors controlling channel form is fundamental to increasing knowledge of channel geometry - discharge relationships and this research focuses on the causes of variability within downstream hydraulic geometry models. Sections 2.6 and 2.7 discuss the factors that may be operating to control channel form and adjustment at different scales.

2.6 Local controls on channel geometry - discharge relations

The variability of factors local to the channel include channel boundary materials and bank stability; bed material and bedload transport; and vegetation and will be considered in the following sections.

2.6.1 Channel boundary materials and bank stability

The shape of river channels has been shown to be influenced by sediment boundary conditions, with bank materials being particularly important in controlling the rate of channel adjustment and processes of channel evolution. Widening of an alluvial channel occurs through bank retreat that is not matched by advance of the opposite bank through bar deposition (Thorne and Osman, 1988). Retreat occurs as a result of lateral erosion by hydraulic action of the flow and mass failure of the bank under gravity. Both processes are dependent on the composition of the channel boundary (cohesive or non-cohesive sediments) and regulated by basal end point control, the concept linking bank processes to sediment transport within the channel.

A distinction may be drawn between cohesive and non-cohesive banks depending on the relative influence of forces of particle weight and surface attraction (Grissinger, 1982). The response of channel banks to disturbing forces is dependent on the cohesiveness of the perimeter sediments. The percentage of silt-clay in the banks determines the cohesiveness of the banks and is important both in terms of lateral erosion and bank stability. Lateral erosion is the detachment of grains or assemblages of grains from the bank surface, dependent on ratio of disturbing to resisting forces. In non-cohesive materials, bank material is usually detached grain by grain and erosion is dependent on interparticle frictional forces acting under the slope normal component of submerged weight (Thorne and Osman, 1988). In comparison, cohesive bank material is usually eroded by the entrainment of aggregates and empirical studies have shown that entrainment depends more on micro scale electrochemical properties of the soil, pore and eroding fluids than mechanical properties such as soil strength in compression or shear. Field and flume experiments have shown that undisturbed cohesive banks with a high silt-clay content are much more resistant to fluvial erosion than are non-cohesive banks.

Schumm (1960) investigated the relationship between bank materials and channel shape in terms of percentage silt-clay content (M) in the channel bed (S_b) and banks (S_c) weighted by the width and depth respectively.

$$M = \frac{[(S_b.w)] + 2(S_c.d)]}{w + 2d} \tag{2.7}$$

Schumm (1960) found that M correlated strongly with channel form ratio F, the ratio of width to depth (W:D). Those channels that contain little silt-clay are relatively wide and shallow, whereas those composed pre-dominantly of silt and clay are relatively narrow and deep. Melton (1961) criticised the F-M correlation on the grounds that the weighted index M includes width and depth in its derivation producing a circular correlation. Ferguson (1973) later re-analysed Schumm's data, suggesting a model which relates width more logically to bank silt-clay content (B) using multiple regression;

$$W = 33.1\ Q^{0.58}\ B^{-0.66} \tag{2.8}$$

Bank stability reflects the bulk mechanical properties of sediment whose shear resistance (S) is a function of cohesion (c') and friction measured by the internal angle of friction ϕ', measured with respect to the effective normal stress σ'. Bank failure occurs when fluvial erosion leads either to bed-scouring at the bank toe which increases the bank height or undercutting which increases bank angle (Thorne and Osman, 1988). Much of the work on river bank adjustment has been involved with the mechanics of erosion and failure of banks at a single reach. For example, Osman and Thorne (1988) developed a slope stability analysis for steep banks in conjunction with a method to calculate lateral erosion to predict the response of bank stability to erosion or bed degradation. The linkage between mass movement, sediment accumulation and consequent removal is approached using process based models which can then be applied to specific geomorphological problems, for example, the prediction of degradation downstream of a dam where bed lowering has caused bank instability (Osman and Thorne, 1988).

The shear resistance of bank materials to failure is dependent on the properties of the bank materials including moisture content, loading and density. Methods of assessing bank erosion in cohesive soils were reviewed by Grissinger (1982) and include measurement of primary soil properties such as mean particle size, clay and organic matter content, type of clay, bulk density and void ratio; and composite soil properties, such as Atterberg limits, penetration, electrical conductivity. In addition, bulk strength properties for example, shear strength and tensile strength, have also been related to stability of cohesive materials whereas other studies have shown that these bulk strength parameters are not related to stability. The variability in results of tests can be attributed to conditions of testing, in particular the hydrological conditions and homogeneity of bank materials.

Schumm (1971) stated that the uniformity of bank materials in a river system results in well-defined width and depth discharge relationships. If M increases downstream, the rate of change of width and depth with discharge will reduce, while if it fluctuates the scatter in width discharge graphs will be considerable. Bank material composition is highly variable and downstream trends are unlikely to be well defined across a broad range of rivers (Knighton, 1998), but research within individual river systems may indicate clear changes in channel adjustment according to bank material type, for example, Dury (1984) detected abrupt variations in channel width along the River Severn, UK, which appeared to reflect local differences in bank strength.

Darby (1994) carried out sensitivity analysis of factors controlling channel geometry for the development of his model of channel adjustment. He found that although discharge was the singular most important factor controlling channel shape with the sensitivity values for other variables calculated to be at least one order of magnitude smaller than discharge, the critical shear stress (τ_c) of river banks was also found to have high sensitivity parameter with regard to width. Bank material cohesion was also found to be an important influence on channel depth and Darby (1994) suggests that bank material characteristics have an important role on both width and depth at different times during the river adjustment sequence. Changes in depth through bed lowering increases the sensitivity of the banks to instability and failure thus increasing channel width. Channel width and depth adjustments are therefore interdependent.

Darby (1994) suggests that the role of bank material characteristics appears to be in influencing the detailed form of the channel within the broad constraints set by the flow characteristics (Darby, 1994). This supports Richards' (1978) statement that discharge is essentially a scale variable determining the absolute size of a river channel while relative measures (channel shape indices) are influenced by other variables. Huang and Warner (1995) also stressed the importance of boundary sediment composition reflected in changes in the coefficients in the relationship between channel shape and channel two-dimensional shear stress. The coefficient value increases by nearly 2.5 times when the sediment composition of the channel changes from gravel to sand, causing a nearly two fold increase in width, but a three fold increase in channel shape (W:D) implying that sediment composition has a greater effect on channel shape as opposed to channel dimensions. However, more work needs to be done in this field and Huang and Warner (1995) suggest that more attention should be directed towards developing a quantitative index to reflect the channel perimeter materials.

Work on regime theory by Blench (1969) incorporated channel boundary conditions explicitly into regime equations with bed (f_b) and side (f_s) factors. Simons and Albertson (1960) also derived regime equations according to bank material type based on the finding that the width coefficient for sandy banks was 33% larger than that for cohesive banks. Other authors have also emphasised the importance of bank materials in controlling width for example, Hey and Thorne (1986) Bray, (1982) and Andrews (1982) who investigated bank stability in relation to scour and fill processes. Darby (1994) recommended that future hydraulic geometry analyses should include observations of bank material shear strength in the analyses of width, depth and slope changes against discharge in a wide variety of streams.

2.6.2 Bed material, slope and sediment transport

Bed material type and size is important in terms of particle mobility, which is related to the transporting capacity of the stream and channel roughness which determines velocity of the channel and stream power. The most effective discharge in terms of sediment transport, sometimes used as the dominant discharge in channel geometry - discharge relationships is dependent upon bedload transport. Bed material and sediment load is derived from three sources; the adjacent hillslope, the river network upstream and the channel banks.

The amount of sediment contributed to the total load of the river depends not only on the boundary shear strength, but also on distribution and types of material in the channel boundary. Gravel and cobble rivers with non-cohesive sand or gravel banks show high rates of lateral erosion compared with bank scouring and in such cases a large percentage of total sediment is contributed to the channel from the banks. By contrast, in sand-bed rivers with cohesive river banks most of the total load comes from the bed (Thorne, 1982). The relationship between sediment load and channel boundary conditions was noted by Schumm (1968) who found a strong inverse relationship between the silt-clay content in the bed and banks (M) and bedload, expressed as the percentage of total channel load. Channels were classified into three classes according to the composition of the channel boundary which reflects sediment transport; bedload channels ($M \leq 5$), mixed load channels ($M > 5 < 20$) and suspended load channels ($M \geq 20$). Channels with high suspended sediment loads tend to have banks with a high silt-clay content, whilst gravel bed rivers with high bedloads tend to be dominated by sand banks.

The size of bed material affects the transport of sediment and thus the adjustment of river channel geometry and slope based on the continuity equation ($Q = w.d.v$). Pickup (1976) argued that an optimal width-depth ratio exists for bed-load transport suggesting that the channel shape adjusts to the whole sequence of sediment bearing flows in order to maximise transport efficiency, whilst channel size is more closely related to the dominant discharge. The type and amount of bedload, related to the boundary conditions within the channel, determine the maximum efficiency of flow controlled by the shape and size of the river. The channel with the maximum hydraulic radius has a semi-circular cross-section, but as Lane (1937), Sundborg (1956) and Schumm (1963) noted bed-load channels tend to have cross-sections which are wide and shallow. Parker (1979) suggests that the quantity of bedload transport is important predicting that for a given discharge a 30% increase in gravel load leads to a 25% reduction in centre depth but a 40% increase in width.

One of the main problems in investigating the effect of bed-load transport is the difficulty of field measurement due to a general lack of gauging stations which measure sediment transport. Wilcock (1971) recognised the limitations before undertaking a detailed study of the relationship between bedload transport and channel shape in the River Hodder, Lancashire, UK. Based on the results, he drew the conclusion that with increasing discharge, competence will tend to increase only when the rate of increase in velocity equals or exceeds the rate of increase in depth. Despite considerable discussion Wilcock (1971) also concludes that the relations between movable bedload and discharge, channel shape and flow characteristics are complicated and other factors such as pebble shapes and packing coefficients must be effectively measured and considered.

The influence of bedload size is important in relation to bedload transport and the flow required to facilitate movement. The entrainment of bedload results in changes in bed elevation and slope, and downstream rates of change in channel slope are therefore closely related to changes in bed material size (Hack, 1957). There is evidence of distinct changes in slope where the bed material changes from gravel to sand. The gravel-sand transition is often abrupt and the discontinuity has implications for channel form adjustment (Yatsu, 1955; Howard, 1980; Kellerhals; 1982).

Finally, the introduction of coarser bed material at tributary junctions can produce changes in channel form both at the confluence itself and further downstream (Knighton, 1998, p. 140). Where a sequence of tributaries enters the stream, grain size and sorting may vary discontinuously in such a way that an exponential decrease below each junction is followed by a stepped increase at the next (Troutman, 1980).

2.6.3 Vegetation

There is a comparatively small literature on the influence of vegetation on river behaviour (Gregory, 1992) and more research is necessary to understand the complex effects of in channel and bankside vegetation. At present there is no procedure to explicitly take into account the effect of bank vegetation when analysing mass failure processes in river banks (Lawler *et al.* 1997) and the effects of vegetation are difficult to quantify in terms of their overall impact on channel form. Hickin (1984) suggested that vegetation exerts an influence on channel morphology through five mechanisms: flow resistance, bank strength, bar sedimentation, the formation of log jams and the occurrence of concave log jams

Vegetation both within the channel and on the banks can affect flow resistance and cause a decrease in velocity. Flow resistance of channels with bed vegetation such as grass and weed growth is related to the height and density of the plant, although the flexibility of plants must be taken into account which reduces its height and thus its resistance (Bathurst, 1997). Bank side aquatics and tree roots also increase channel boundary roughness and flow resistance within the channel.

Vegetation build up within the channel can also have a significant impact on channel morphology, especially in wooded areas. In channel organic accumulations of Coarse Woody Debris (CWD) can have a varied morphological response. Build up of CWD, often referred to as debris dams affect the routing of discharge, especially of peak discharges, along the channel (Gurnell and Gregory, 1984) causing localised scour and bank erosion and changes to patterns of sediment transport and storage. Vegetation build up above debris dams or on gravel bars can lead to the trapping of finer sediments allowing re-vegetation of mid-channel and side bars. This can stabilise depositional features within the channel and influences low flow patterns and channel adjustment during bankfull flows. Gregory (1992) highlighted the importance of debris dams in terms of travel times through the river system, sediment storage and ecological processes. The removal of dams can lead to loss of important habitats, bed sediments and cause increased erosion, damaging to the channel.

The effect of vegetation on bank stability is complex and cannot be classed as a benefit or liability without consideration of the type, age and density of the vegetation (Thorne and Osman, 1988). Thorne (1990) and Thorne and Osman (1988) argue that vegetation can either decrease or increase bank stability, depending on the type of vegetation, bank geometry and materials. The roots and rhizomes of grass and shrubs reinforce the soil enhancing bank stability with regard to shallow failures. Soil is strong in compression whilst roots are strong in tension so combined, increase the overall strength of soil. However, the increased strength only extends to the depth of the root system so vegetation of this type has little or no affect on the stability with respect to deep seated failures (Thorne and Osman, 1988). Trees are more deeply rooted and can affect the stability with regard to deep seated failures. Whether a given tree is a benefit or liability depends on the type of tree, the bank geometry and the density of trees along the bank. Bank angle has a bearing because on steep, undercut banks the detrimental effect of the weight of a tree more than offsets any benefits through soil reinforcement so that the tree is a net liability. Bank height is significant in terms of rooting depth. If the roots cross the potential failure plane reinforcement can be effective. A continuous band of trees is far more effective in enhancing bank stability.

2.7 Catchment controls on channel morphology

To understand channel behaviour at the reach scale it is important to consider catchment characteristics and the influence of drainage basin form on channel morphology. The topography of the catchment can have a direct effect on channel morphology but also indirectly effects the channel through its influence on vegetation and landuse that determine the hydrological regime of the catchment.

2.7.1 Drainage basin form

Valley slope, defined as the longitudinal slope of the valley measured along the main valley axis, may control the adjustment of local channel gradient, thus influencing in channel depth and width. The long profile is largely an inherited characteristic related to past flow conditions and therefore imposes an external control on channel form. Despite an overall tendency to decrease downstream from the headwaters to the source, the slope of the valley floor can vary significantly as a result of non-alluvial effects such as changes in underlying geology or past high magnitude low frequency events.

Lateral changes in the catchment morphology downstream are also important, particularly the development of the floodplain. The catchment must therefore be investigated at different scales as shown in figure 2.2. The width of the valley can indicate the type of hillslope hydrology and the degree of coupling between the channel and the valley sides. Small headwater tributaries usually flow within steep sided V shaped valleys. Further down the river network the valley sides tend to be less steep and the valley bottom is often infilled with sediments (Gilvear, 1996). The river is often separated from the valley sides by more or less extensive floodplain. Where the channel is confined, particularly in small headwater reaches, deepening may be the dominant change and adjustments to planimetric form may become somewhat limited (Anderson and Calver, 1977).

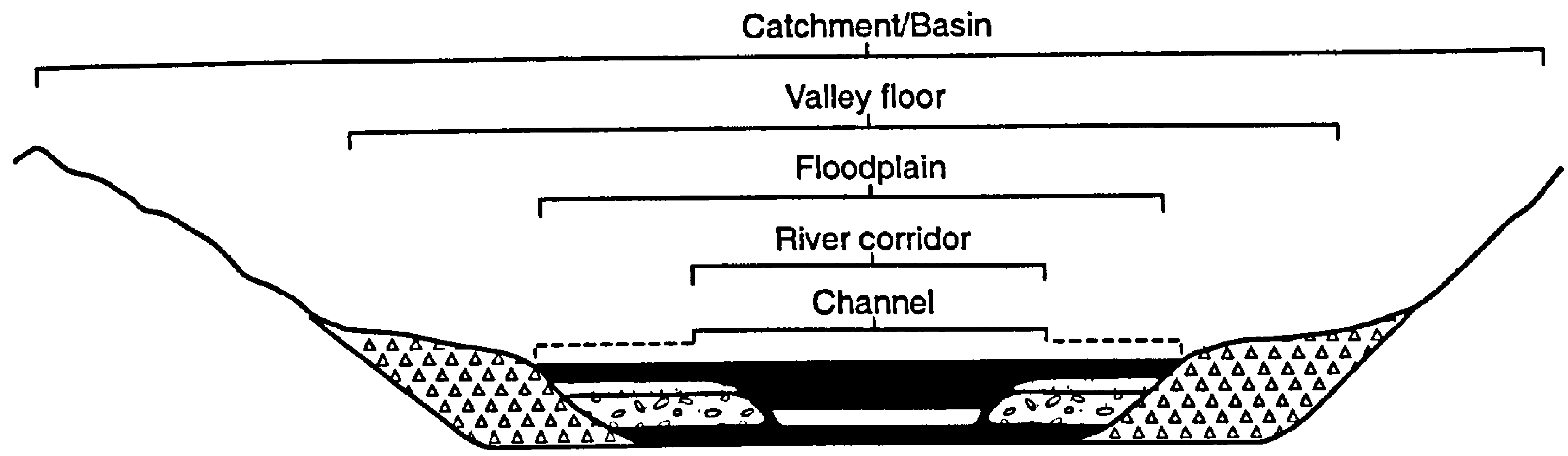


Figure 2.2 **Cross-section of a river valley to show different lateral zones. Source : Newson (1992)**

The degree of channel-hillslope interaction (coupling) is important in terms of the composition of bed material supplied to the channel. Within the drainage network the composition of bed material supplied at any point to the channel may be primarily alluvial, delivered by flowing water from upstream or colluvial delivered by gravity from the hillslopes. The frequency of inputs of non-fluvial sediments into the channel reflects the degree of coupling between the hillslope and such sediment sources are likely to be most common in the headwater reaches (Church, 1983). Further downstream, discharge increases allowing the transport of colluvial material, and the development of the floodplain acts as a buffer between the hillslope and the channel. Where the floodplain is fully developed, the channel can be described as completely buffered so that the only form of sediment entering the channel is from the channel banks or alluvial material from upstream (Rice, 1994). Most channels are characterised by intermittent links that are neither strongly coupled nor strongly buffered, but intermittently coupled downstream. The floodplain is also important as a sink for suspended sediment transported during peak flow events. The transfer of energy and sediment from the channel to the floodplain influences floodplain development and channel planform (Marriot, 1998).

Richards (1980; 1982) considers the influence of drainage network organisation on hydraulic geometry and suggests that an alternative model to conventional downstream channel geometry. It assumes a continuous adjustment of channel dimensions downstream which should take into account the adjustments that occur at tributary junctions (shown by discrete steps in the downstream trend line). Rivers adjust their morphology in a downstream direction partly in response to the water and sediment supplied by tributaries. Pizzuto (1992) points to the dependence of downstream hydraulic geometry on network topology (Clifford, 1996) and the assessment of hydraulic geometry within the catchment context, discussed in relation to channel morphometry (section 2.5), remains an area for further research.

2.7.2 Flow variability

The concept of dominant discharge has provoked several studies investigating the significance of flow variability on cross-sectional from. The use of a single reference discharge is necessarily an over simplification of the relationship between channel form and discharge and does not represent the full range of morphologically significant flows. In all climates, but semi-arid areas in particular, the magnitude, frequency and timing of flood events are fundamental to the understanding of morphological adjustment.

In those rivers where flow regime is variable, that is, the ratio of individual flood peaks to mean annual flood (Q_p/Q_{maf}) is large) or where the channel boundary is highly resistant, the concept of dominant discharge and related concept of channel equilibrium may become less applicable (Stevens *et al.* 1975; Baker, 1977). In these cases the channel may exhibit non-equilibrium tendencies.

Harvey (1969) investigated the influence of the hydrologic regime on channel geometry in three UK catchments. Results from the Wallop Brook, the River Ter and the River Nar, showed that all the channels appeared to be influenced by the differing flow regimes. In the River Ter and Upper Nar, streams with an important peakflow element, equilibrium geometry appeared to be maintained by the mean annual flood. However, in the Wallop Brook a baseflow dominated stream, the cross-sectional form was related to much rarer flood events. Harvey proposed two explanations for the difference in channel behaviour in the three rivers. First, the importance of frequent flows in obscuring the effects of larger peak flow events through processes of aggradation in streams with variable flow regimes; and second, on the difference between the duration of flood events in baseflow and non-baseflow dominated streams.

Osterkamp (1980) found that rivers with a flashier regime and relatively high peak flows tend to develop wider channels. However, Yu and Wolman (1987), also investigating the relationship of channel geometry to measures of streamflow variability, found that greater variability was associated with narrower channels. Their work was based on the idea developed by Pickup and Reiger (1979) that the channel form reflects antecedent flows and the channel has a *memory* which exists until discharge exceeds current channel capacity, highlighting the importance of the whole range of flows. Yu and Wolman (1987) developed a simple simulation model from which a series of channel forming discharges are produced and corresponding channel geometries were calculated. Flow variability was also calculated using two discharges using different return periods for a specific probability distribution (see Yu and Wolman, 1987). When the model was tested, the results showed that the width predicted by the model, for a given discharge, is in general narrower for channels with a high flow variability (CV >1.5) than for rivers with a relatively low variability (CV < 1.0). Yu and Wolman (1987) suggest that the effect of existing geometry on forthcoming channel forming events lies in its determination of whether or not the discharge can exceed the critical flow magnitude needed to alter the existing channel form. For example, if the channel has been previously enlarged by a high magnitude, low frequency event it will tend to remain overlarge relative to future discharge, so that a discharge that might have previously enlarged the channel may now actually reduce it by depositing sediment. Work by Knight (1992) which aimed to investigate the findings of Yu and Wolman (1987) using flume experiments did not find any conclusive evidence to suggest that flow variability could be associated with varying channel geometry.

The sequencing of the flow events also influences the nature of channel adjustment. For example, two flood events in quick succession result in a different geomorphological response from two flood events occurring a couple of months apart. Rhoads and Miller (1991) investigated the impact of sequential flow of various magnitudes on the morphology of the low energy Des Plaines River in Eastern Illinois, a stable humid, temperate environment. They assessed the stability of the river channel and carried out t-tests to evaluate the hypothesis that mean changes in width and depth along the reach were zero for each measurement interval. They found that the 1 in 100 year flood event did not significantly alter channel width contrasting with previous studies, but that bankfull conditions were nearly as effective in altering channel form as the estimated 100 year flood. Channel depth decreased in 18 out of 23 cross-sections and although showing a small net increase it was statistically significant due to low variability about the mean. The subtle geomorphological changes are attributed to the low energy nature of the river, low hydrologic variability, fine bed materials and cohesive banks. Rhoads and Miller (1991) suggest that the temporal ordering of events is significant. The problem of changing channel geometry due to varying streamflow is not solved (Yu and Wolman, 1987) but could be an important factor influencing channel geometry - discharge relations, especially in rivers of certain regimes, for example, baseflow dominated.

2.8 Variability of channel geometry - discharge relationships

The influence of independent variables at both catchment and local scales may be represented by the variability in channel geometry - discharge relationships. Research on channel geometry - discharge relations for the prediction of stable channel dimensions, has focused on improving the applicability of design equations by reducing variability around the regression line. This has been approached by incorporating independent factors controlling river channel form explicitly into design equations using multivariate regression relationships. For example the inclusion of bed material size (Kellerhals, 1967; Charlton, 1978) or alternatively by developing channel geometry - discharge equations according to varying environmental conditions for example, vegetation type (Hey and Thorne, 1986) or bank composition (Simons and Albertson, 1960). Equations developed using data from gravel bed rivers which predict river channel dimensions from one or more independent variables (the primary variable being discharge), remain in practise for river channel design procedures, (Guidelines for design and restoration of flood alleviation schemes, 1993). However, many of the channelisation schemes based on traditional regime type or downstream hydraulic geometry equations have resulted in severe geomorphological and hydrological problems (Brookes, 1987a, 1988, 1995b). Reeves (1994) estimated that perhaps in only two out of three channels can the equations predict channel dimensions to within 33% of the actual values. This suggests that variability of channel geometry - discharge relationships is significant and requires further investigation in terms of what it represents and its significance for river channel design and management.

Research into variability between channel geometry - discharge relationships, was investigated on a world-wide scale (Park, 1977; Rhodes, 1977, 1987) by examining the simultaneous variation of hydraulic geometry exponents using triaxial diagrams and identifying possible controlling factors. The result of plots of b, f and m exponents from width depth and velocity relationships with discharge worldwide was huge scatter that cannot be explained by differences in curve fitting techniques. Park (1977) sought, but did not find, systematic variation according to environmental factors such as climate and river type. Rhodes (1977) looking at at-a station variations noted that b<f at 90 per cent of sites implying a fall in width/depth ratios with increasing discharge and also some separation of b, f and m envelopes according to channel pattern. In his later paper, he focused on variation in exponents downstream and emphasised 12 common sets of hydraulic responses to discharge and sediment load. Variation of the exponents at a local scale was found to be also widespread and one criticism of hydraulic geometry is the inherent contradiction of using mean values and regression trends to identify similarities when variability is more common (Clifford, 1996). Knighton (1974) also noted the importance of understanding the spatial variation in material and flow conditions as they influence the change of width, resulting in variation in the b exponents both along and between rivers and emphasised the importance of looking at within catchment variation.

The investigation of exponent values compares various channel geometry - discharge relationships derived from data from different environments. To investigate the influence of controlling factors on channel geometry discharge relations as suggested by Park (1977) and Rhodes (1977,1987), it is necessary to examine the variability within a single hydraulic geometry relationship which is derived using regression analysis. Regression analysis can be used in three main ways; first to establish a predictive model, the case with the channel geometry - discharge regression model, in which the geometry of the channel is predicted from the discharge; second to test a model or hypothesis; and third to describe the relationship between variables (Shaw and Wheeler, 1985). It is a widely used technique within environmental science but is limited by several important assumptions. 1) The independent variables should not, if possible, be sample measurements and if they are should have been measured with a negligible amount of error. 2) Variance of the dependent variable is constant for all values of the independent variable. 3) The value of the residuals have a normal distribution and are independent of each other, i.e. that they are randomly arranged along the regression line (Ebdon, 1977).

The regression model of the form y = a + Qb is an average relationship between channel geometry and discharge based on the least squares regression line fitted through a graphical plot of observed data. Each point on the graph represents the observed values at an individual river reach. When the observed value (Y) for the dependent variable, in this case width, is compared with the value predicted by the model for a given discharge (Yi), the difference is termed as a *residual*

$$Yres = Y - Yi \tag{2.9}$$

For the purposes of this research the residuals were standardised to allow comparisons to be made between residual values. The residuals are expressed in terms of the normal distribution (discussed further in Chapter 4, section 4.3.4).

The residual values represent the points of variance around the regression line that the model cannot explain and are therefore caused by factors other than the independent variable. The residuals can be differentiated by their direction shown in figure 2.3 and magnitude.

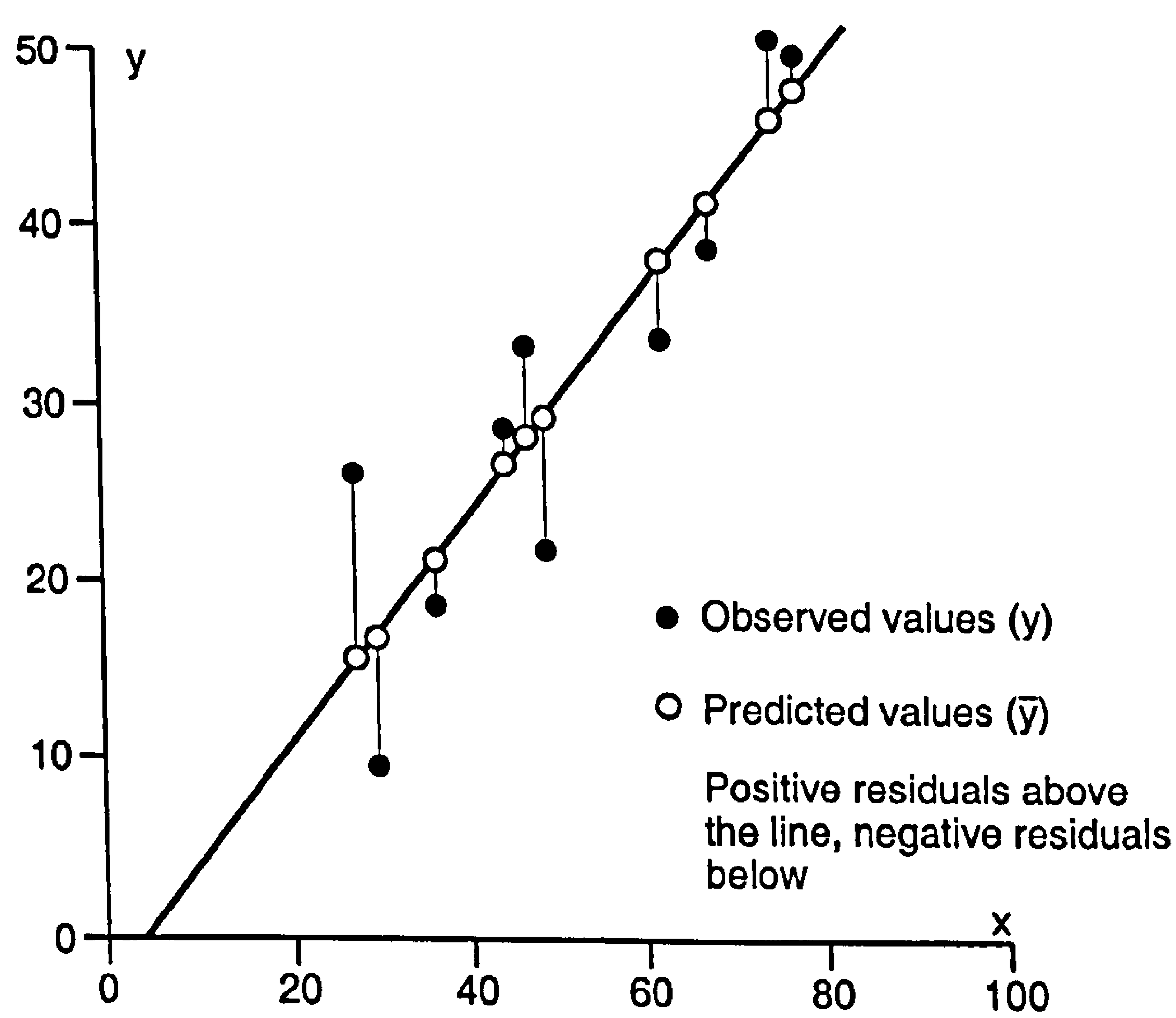


Figure 2.3 **The difference between positive and negative residual values**

The points lying above the line are *positive* residuals where the observed width is greater than the predicted width and the channel is over-wide when compared with the regression model. The points lying below the line are *negative* residuals where the observed width is smaller than the predicted width and the channel is under-wide when compared with the predicted model width. The residual therefore indicates the extent to which the channel is under or over-wide in relation to the model. Residuals closest to the line show least deviation. With increasing residual magnitude the difference between observed and predicted width increases.

There has been little detailed investigation of the variability of channel geometry discharge relationships indicated by residual values. Variability is important both in terms of what it represents and also in terms of the use of an average relation for channel design. Wharton (1989) suggested that residuals from channel-geometry discharge relationships for the estimation of flood magnitude may be indicative of environmental factors or sensitivity to change. Reeves (1994) began initial investigations using the residuals from a regression model based on data compiled by Wharton (1989) and found that there was a significant variation in residuals suggesting that one or more morphological factors may be having an effect. In line with Wharton's (1989) findings there was a greater frequency of negative residuals, where the regression model underestimates the width suggesting that the majority of factors causing higher residuals are those which restrict width. Preliminary field investigations were carried out at several sites of high residual magnitude to examine whether the residuals have any geomorphological significance. Five factors were selected by Reeves (1994) as influencing residual values; resistance of the bank to vegetation; flow regime; stability of the reach; human influence; equivalence of the most effective discharge and reference discharge.

2.9 Summary

The relationship between channel geometry and a channel forming discharge has been shown to be significant in many different environments (Bettess and White, 1987; Darby, 1994; Wharton, 1995). Despite the strength of this relationship, variability around hydraulic geometry models remains and there has been little investigation into what this variability represents and its importance in terms of the use of design equations based on hydraulic geometry. The knowledge that, "improper design may well introduce instability into artificial channels, of such magnitude that it is not economically feasible to operate them"(Simons and Albertson,1960, p.66), has lead to a need for more understanding of the geomorphological processes and environmental factors which operate to control river channel form and adjustment. More research is necessary on the factors controlling the relationships between channel geometry and discharge and the extent to which they affect the accuracy of downstream hydraulic geometry equations. The state of the river channel may also affect the relationship between channel form and discharge. The factors which control river channel stability must also be considered in terms of the choice of river channel design methods and the sensitivity of the channel to change and will be considered in Chapter 3.

CHAPTER 3

RIVER CHANNEL STABILITY AND SENSITIVITY TO CHANGE

3.1 Introduction

Understanding the way in which channels change from one state to another in response to internal and external changes is crucial for river management, restoration and conservation. Flood control and maintenance of river systems are based on predictions of short-term channel adjustment. In terms of restoration and conservation, knowledge of stability is fundamental since the ability of a landform to absorb change profoundly affects the development of an appropriate conservation strategy (Werrity and Brazier, 1992).

There is considerable ambiguity concerning the definition of stability and the terminology used to describe a river reach. There is confusion surrounding the classification of rivers according to the degree of naturalness and the stability of the channel. Referring to a river channel as natural does not necessarily mean it is in a stable condition. Similarly a channelised river cannot always be assumed to be stable, in other words the state of a river cannot be determined by the condition of the channel or the degree of naturalness. Many authors have set out criteria by which to classify a river reach, but the imprecision with which terms such as natural, stable and sensitivity are used is the cause of many of the problems associated with the assessment of river systems so fundamental to their design and management. The importance of assessing the stability of channels in relation to the flow regime is crucial in terms of river channel design and restoration. This chapter seeks to clarify the terms used to describe the condition and state of river channels and discusses the concepts of naturalness, stability and sensitivity.

3.2 The definition of natural

To study the relationship between channel geometry and discharge, it is necessary to examine river sites that are free to adjust their form in response to the prevailing flow regime. This condition is often referred to as 'natural', but the frequent use of the term to describe rivers which may not be completely natural, has led to debate about what constitutes a natural river and the need to clarify the terminology surrounding the channel condition. The Oxford English Dictionary defines natural as;

> "Existing by nature; not artificial; innate; inherent; self sown; uncultivated."

In fluvial geomorphology, a natural channel conforms to the above definition, that is, a channel that has naturally evolved with no human intervention. Richards (1982) refers to channelisation in a way which clearly indicates that any channel that has undergone engineering work cannot be classed as natural;

> "widening, deepening or straightening of natural streams (channelisation) have often been undertaken to improve navigability or accelerate the passage of flood peaks"

Other authors have defined the differences between natural and channelised rivers more explicitly, for example, Corning (1975).

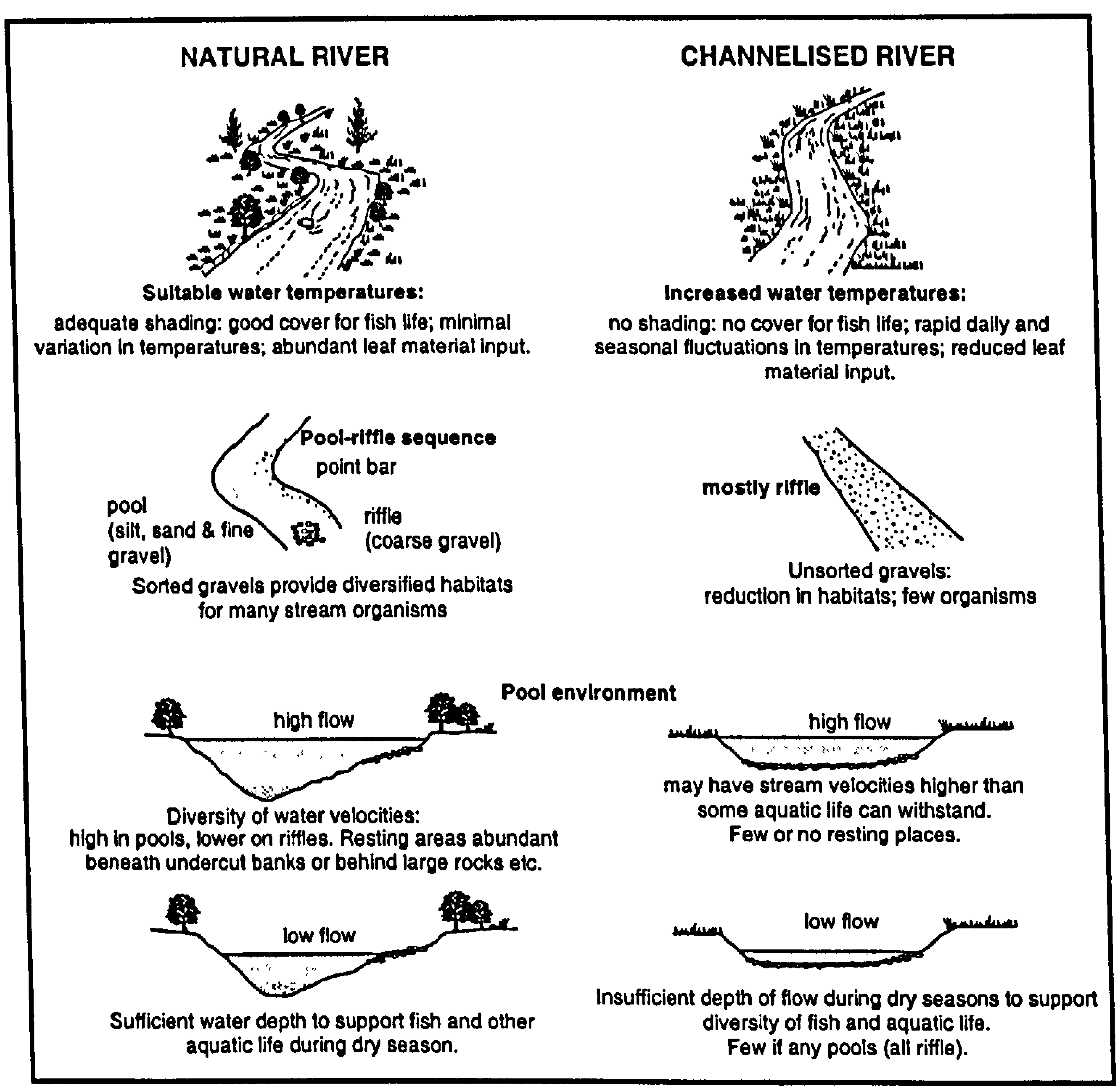


Figure 3.1: Differences between natural and channelised watercourses, Brookes (1988), p.112 based on Corning (1975).

Figure 3.1 illustrates the differences between a natural and a man-made channel in both cross-section and planform, the natural channel referred to as distinct from any river in which engineering works have had an impact, either directly or indirectly. The differences are clearly identifiable in figure 3.1, but the difficulty of definition remains when classifying rivers which have been altered from their natural state, but continue to retain many of their natural features. It is also important to consider the alteration of natural processes as a result of landuse changes in the catchment or the impacts of upstream engineering which could have an indirect effect on channel form at a reach (Brookes, 1988 p.250). Most rivers in the UK have been affected by some form of human intervention or changes in catchment conditions but in many cases, generally where engineering took place some time previously, the channel is freely able to adjust to the changes imposed. It is therefore necessary to define river states according to degrees of naturalness or modification.

The term semi-natural has been used in several different ecological and hydrological contexts, to describe components of the environment which have been affected to some degree by humans, for example, woodlands. *Semi-natural* woods are composed of native tree and shrub species which derive pre-dominantly from natural regeneration processes as opposed to planting. They cannot be described as fully natural as they have often been subject to centuries of management which modifies both the structure and composition of the forest, with the planting of trees introducing species which may not be inherent to the region. The same concept can be applied to rivers. Semi-natural river channels remain pre-dominantly natural in both form and process, but human intervention has caused the alteration of the river channel from its original condition. Rivers often re-adjust to external changes imposed on the system so that after a period of time has elapsed the constraints imposed on the channel are absorbed into the fluvial system. Although the channel does not remain in an undisturbed condition, through time the behaviour of the river can self adjust to allow a semi-natural condition to evolve. The term naturally adjusted has also been used to describe rivers in this condition.

The term semi-natural was used and defined in the River Habitat Survey (RHS) a national survey undertaken by the National Rivers Authority to assess the habitat quality of rivers and streams based on their physical structure. The survey contains information about the physical features, general characteristics and geomorphological processes from a national network of 3000 UK sites, stored in a computerised database. Each site is a standard length of 500m and data about the broad characteristics of the river are recorded for the whole reach. More detailed information about attributes such as channel substrate type, presence of key habitat features and the type of artificial modification are recorded at ten equidistant spot checks along each 500m reach. From this database, a classification divides rivers into segments of one or more types of similar physical character. Based on the sites surveyed in 1994 the classification was initiated by isolating those sites which appeared to be most natural, that is those with little or no obvious modification affecting the structure or flow (River Habitat Survey report, 1996). Only 10% of reference sites were completely free from modification to the channel or banks. Given the need for a larger number of sites for analytical purposes within the RHS, a semi-natural subset was selected based on sites where modification was recorded in no more than one spot check in each 500m survey. This yielded 478 semi-natural river sites across England and Wales.

In the River Habitat Survey, the degree of naturalness or artificial modification over each 500m length of river was expressed by a Habitat Modification 'score' which quantifies the condition of the river. In the scoring system, sites with no human intervention, termed as pristine sites, received a score of '0'and those sites which had been channelised scored 1 or more according to the type of modification. For example, sites that had been resectioned were given a score of 1 for each resectioned spot check and those that had been reinforced were a given a score of 2. The cumulative score for each 500m reach broadly reflects the extent and severity of artificial modification. Semi-natural reaches are defined as those sites where modification was recorded in no more than one spot check, thus scoring from 0-2 on the naturalness index. The more heavily modified sites can score up to 45 or more points.

Other methodologies for classifying rivers in terms of morphology and the degree of alteration include that proposed by Brookes and Long (1989) and used for geomorphological surveys in preparation for restoration schemes in the Environment Agency Thames region. The geomorphological surveys record data on cross-sectional form and planform, information on previous engineering works and stability, the degree of adjustment and recovery from those works and information from the wider catchment (NRA, 1995). Each reach surveyed was classified according to the degree of naturalness based on information on channel modification.

Table 3.1 The sensitivity index used for geomorphological surveys (Brookes and Long, 1989)

Scale	*Channel Sensitivity*
0	Channelised , lakes and navigational
1	Low sensitivity
2	Low sensitivity
3	Low sensitivity
4	Low-moderate sensitivity
5	Moderate sensitivity
6	Moderate sensitivity
7	Moderate-high sensitivity
8	High sensitivity
9	High sensitivity
10	High sensitivity

Table 3.1 shows the index used to classify channel sensitivity that in this case reflects the degree of naturalness. Low sensitivity reaches are those which have experienced substantial alteration e.g. flood alleviation works, agricultural drainage. They are already controlled and altered and therefore would not be greatly damaged by more change. Moderate sensitivity reaches are those that have experienced a degree of modification but have retained many natural features e.g. substrate, asymmetrical profiles. Highly sensitive reaches are usually stretches with little or no channelisation which are extremely sensitive to management or improvement schemes. This system uses the condition of the reach or the degree of naturalness to infer the sensitivity to change. The word sensitivity in this context is misleading because it is referring to the condition of the reach and not the geomorphic sensitivity that is related to channel stability. It does not necessarily follow that simply because a reach is unaffected by channelisation, it has a higher sensitivity to change in the future, which is what the sensitivity index in table 3.1 implies. This highlights the importance of clear definition of the terms used to describe a river reach and the context in which they are used.

HR Wallingford (1992) put forward a methodology for the specification of a river reach described by Thorne et al (1996). The terms used to describe the degree of naturalness at a river reach are shown in table 3.2. The terms in brackets are the definitions that will be used in this project and have been defined in the literature above.

Table 3.2 Terms used to describe channel condition (HR, Wallingford, 1992)

Terms	*Usage*
Pristine *(natural/semi-natural)*	The channel is geomorphologically active and is either in a pristine untouched condition or has fully recovered from past engineering.
Engineered and recovering naturally *(naturally adjusting)*	The channel has been engineered but is recovering naturally from past interventions.
Engineered and terminal *(inactive/fully channelised)*	The channel is unable to recover from past engineering or is prevented from doing so by existing channelisation.

Graf (1996) highlighted the importance of defining the degree of naturalness in terms of river restoration. One of the crucial questions facing geomophologists when restoring rivers is what is natural? In response to this, Graf (1996) developed a classification of geomorphic naturalness based on river systems in the USA, shown in table 3.3. Graf (1996) incorporates changes in sediment supply throughout the river network which influence natural processes operating at the reach, stressing the importance of considering the reach in terms of the catchment.

River channel sensitivity is concerned with the propensity for change within a river system and is partly dependent on the *condition* (naturalness) of the channel but must also consider the *state* of the river system.

3.3 River channel stability

The state of the river channel is not necessarily dependent on the degree to which it has been modified. Channelised rivers are designed with the objective of achieving a stable state, but conventional engineering has been shown in many cases to cause instability both at the engineered reach and downstream (Brookes, 1988). Although rivers in a more natural condition are free to adjust, stability is not always attained. Some rivers are inherently unstable and may never achieve a stable state. The degree of naturalness in

Table 3.4 **Geomorphic 'naturalness' classification for river channels**

Channel type	*Completely natural*	*Essentially natural*	*Partly modified*	*Substantially modified*	*Mostly modified*	*Essentially artificial*	*Completely artificial*
Pattern, cross-sectional shape, materials	No obvious evidence of human activities - same form and processes as existed prior to human occupation	No obvious evidence of human activities - same forms as prior to human occupation	Altered channel patterns, x-sectional shapes, or sediment characteristics as a result of human activities	Altered channel, x-sectional shapes, sediment result of human activities	Altered channel patterns, x-sectional shapes or sediment characteristics as a result of human activities	Altered channel patterns, x-sectional shapes, or sediment characteristics as a result of human activities	Completely engineered and/or built channel with altered processes and sediment
Minor landforms	Same forms and processes as those found prior to human occupation	Altered by human activities or changes in sediment supply	Altered by human activities or changes in sediment supply	Altered by human activities or changes in sediment supply	Altered by human activities or changes in sediment supply	Altered by human activities or changes in sediment supply	Altered by human activities or changes in sediment supply
% Channel area engineered or disturbed	0	<10%	<10%	>10% <50%	>50 <90%	>90% <100%	100%
Descriptive notes	Completely undisturbed channel, could be a wild river in the Wild and Scenic System	Minor modifications by human action, sometimes through flow regulation; in other cases, scattered structures on an otherwise undisturbed channel	Obvious modifications by flow regulation of altered sediment supply resulting in channel disturbed by mining, metamorphosis, scattered structures	Major modifications to channel forms and processes with up to half the channel area disturbed by mining, development, or structures	Major modifications to channel forms and processes, with most of the channel area including dredging; a development, or structures	Largely artificial channel due to engineered bed and/or banks; in some cases including dredging few natural forms or processes remain	Channel completely determined by design and manipulation with no channel forms

the channel cannot be equated with stability and it is therefore important to draw a distinction between the two when considering the sensitivity of the river to change. Stability is based on the concept of equilibrium that has been applied to fluvial geomorphology, although as section 3.2.1 shows, with several different approaches.

3.3.1 The concept of equilibrium

The concept of equilibrium is central to geomorphology but is more often a source of confusion than enlightenment (Thorn and Welford, 1994). The controversy surrounding equilibrium has several explanations. Firstly, multiple meanings of the term equilibrium exist across the physical sciences. Although widely used in thermodynamics, mathematics, general systems theory and geomorphology, the term cannot be applied universally. Within geomorphology the term is frequently used qualitatively rather than quantitatively and this has led to imprecision especially when attempting to draw parallels with other physical systems. Finally, practical problems associated with testing for the existence of equilibrium explain the semantic difficulties that have characterised theoretical definitions. As the concept of equilibrium in geomorphology has evolved it has splintered and overlapped as authors have simultaneously tried to incorporate ideas founded in dynamics and the laws of general systems theory. There have been several reviews of the use of equilibrium (Chorley and Kennedy, 1971; Howard, 1982, 1988; Renwick, 1992; and Thorn and Welford, 1994; Ahnert, 1994) and the following section will identify some of the key issues surrounding equilibrium in the context of this research.

The origins of equilibrium in geomorphology are found in Gilbert's (1877) paper on the Henry Mountains in which he describes an 'equality of action' when the ratio of erosive action becomes equal to the ratio of resistance and an equilibrium is reached. There are several characteristics to be recognised in Gilbert's conceptualisation of dynamic equilibrium, first, the principle of negative feedback, encapsulated in the idea of grade. Negative feedback is a self regulating mechanism which states that a change undergone by any of the factors governing the behaviour of a system will result in a compensating change in the opposite sense to absorb and halt the effects of the original change (Chorley *et al.*, 1984). Gilbert (1877) used the concept of negative feedback to explain the condition of a graded stream that occurs when the channel is at maximum transporting capacity and will neither erode or deposit unless the inputs of discharge and sediment change. Negative feedback operates to maintain this condition; for example, if a steeper channel reach is encountered, the accompanying increase in velocity will lead to an increase in the entrainment of bed sediment resulting in the lowering of channel gradient through bed degradation. When the channel returns to a less steep section, the opposite will occur, with a decrease in velocity resulting in the deposition of sediment and an increase bedslope. In this way the stream tends to equalise its work of erosion, deposition and transportation, producing equilibrium, termed as *grade.*

Gilbert's idea of grade is the earliest example of the concept of equilibrium and is generally thought of as the forerunner to the characteristic-form idea (Brunsden and Thornes, 1979). The concept in both cases resembles the balance of forces equilibrium found in dynamics, by analogy rather than formal derivation. In dynamics, equilibrium is founded in Newton's laws of motion and thereby embraces the concept of force, where force is defined as mass times acceleration, that is the change in motion of an object. Other states of equilibrium can also be described in terms of force acting upon a net object and can be seen in figure 3.2.

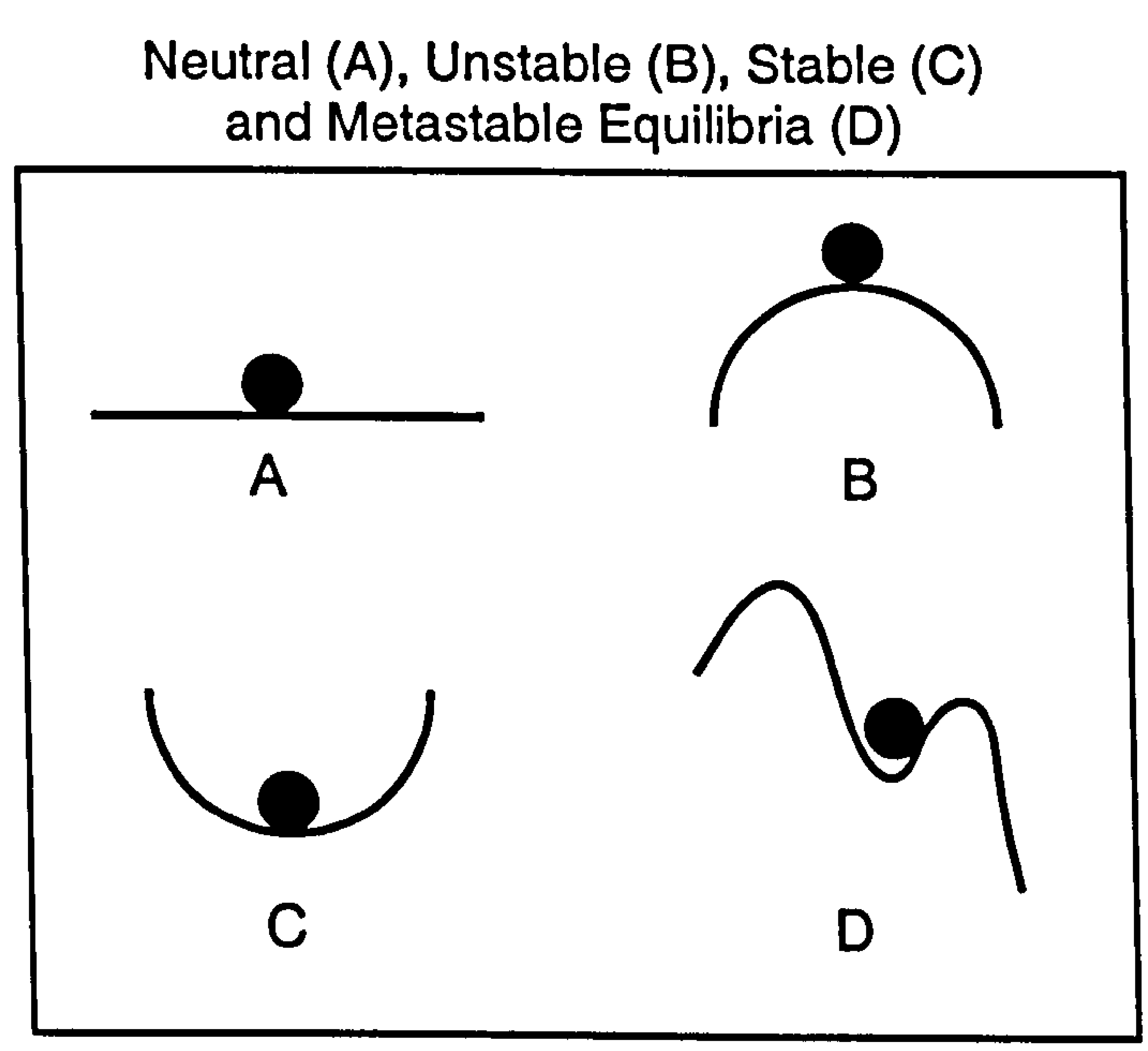


Figure 3.2 Schematic diagram of an object in neutral equilibrium (A), unstable equilibrium (B), stable equilibrium (C) and metastable equilibrium (D). The underlying surface may be considered to be a potential energy surface (Thorn and Welford, 1994).

Neutral equilibrium arises when a small displacement of an object results in no net force on that object. Unstable equilibrium occurs when an object is located in a position where a small displacement results in a net force acting in the same direction as the initial displacement - a characteristic of positive feedback. In stable equilibrium, a small displacement produces a conservative or restoring force which operates in the opposite direction to the displacement (negative feedback) to produce equilibrium. Finally, metastable equilibrium occurs when an object is located in a position where small perturbations result in stable behaviour, but larger perturbations result in unstable behaviour followed by stable behaviour in the new equilibrium position (Thorn and Welford, 1994). This concept of equilibrium displayed in terms of a balance of forces was used applied to geomorphology by Brunsden and Thornes (1979).

This idea of stability progresses from Gilbert's early idea of dynamic equilibrium which must be regarded as uniquely geomorphic in approach, characterised by a description of process, a statement of condition, scale dependency and a focus on the transfer of mass as opposed to energy (Thorn and Welford, 1994). Gilbert's work directly contributed to the establishment of the idea of negative feedback and the utilisation of mass as metric, founded on the principles of dynamics. However, the significance of his insight was overwhelmed by the Davisian theory of landscape evolution, based on the closed system approach where time is the controlling factor.

Mackin (1948) shifted away from the Davisian paradigm and defined a graded stream as one which "over a period of years slope is delicately adjusted to provide, with available discharge and prevailing channel characteristics, just the velocity required for the transportation of load supplied from the drainage basin". Mackin (1948), although retaining some characteristics of Davis's model by implying that velocity decreases downstream, made the important move away from using time as the principle controlling variable. He distinguished long term balance from short term adjustment with emphasis on the river as part of the drainage system. His idea of grade was an intermediate step between the qualitative approach and a revival of the concept of dynamic equilibrium in the 1960's associated with the quantitative revolution. Much of the confusion that has occurred since in geomorphic thought has resulted from the fusion of several different equilibrium concepts from different backgrounds (Thorn and Welford, 1994). The main problem highlighted by Thorn and Welford (1994), has been the merging of the terms 'dynamic equilibrium', a geomorphic concept and 'steady state' a strictly thermodynamic one, initiated by Hack (1960). Leopold and Langbein

(1962) continued mixing the terminology consolidating the errors of Hack (1960) in their statement that

> "The steady state possible in an open system differs from the stationary state of static equilibrium of closed systems. We shall therefore equate the term steady state with dynamic equilibrium in geomorphology as defined by Hack (1960)".

This incorporates three separate concepts: steady state referring to an open thermodynamic system a stationary state defined with respect to energy alone; static equilibrium defined within dynamics as a body which is stationary and where the sum of forces is zero; and finally Gilbert's dynamic equilibrium, the adjustment of landforms between the processes of erosion and bedrock resistance (Thorn and Welford, 1994). Much of the literature since (Abrahams, 1968; Ahnert, 1967, 1988; Chorley and Kennedy, 1971) has been concerned with redefining dynamic equilibrium in a manner that is compatible with terminologies in other disciplines although the issue still remains confused. Chorley and Kennedy's (1971) definitions of types of equilibrium followed a systems approach in which dynamic equilibrium is linked with steady state. This set of definitions has been used for some time and dynamic equilibrium has become established as a condition of fluctuation around the mean which is itself continuously trending through time for example, linear increase. Ahnert (1994), however, makes a distinction between the mass budget equilibrium and dynamic equilibrium that applies strictly to the equilibrium between processes that are the expression of forces within the system. For example, the term 'dynamic equilibrium' is out of place when applied to relationships between non-process components of process response systems (Ahnert, 1994). The difficulties surrounding the use of the terms adopted by Chorley and Kennedy (1971) can be avoided by using definitions which are geomorphically derived and are based on the balance of forces, for example, Renwick (1992).

Renwick (1992) differentiates between equilibrium, disequilibrium and non-equilibrium and returns to a purely geomorphic distinction (figure 3.4). Equilibrium is not a static state but a geomorphic form displaying relatively stable characteristics. Disequilibrium is an adjustment towards equilibrium, but because response times are relatively long, there has not been sufficient time to reach such a state. Non-equilibrium refers to a state where there is no tendency towards equilibrium and therefore no possibility of identifying an average or characteristic condition. Non-equilibrium caused by positive feedback mechanisms occurs when a change in the system is magnified by the system operation such that its effect is enhanced or continued and the system cannot attain equilibrium (Chorley *et al.*, 1984). Chaotic non-equilibrium is where the system oscillates randomly and never reaches an equilibrium state. Non-equilibrium can also be threshold dominated where a trend through time is subject to step-like discontinuities as a threshold effect operates to promote a sudden change of form. Threshold dominated non-equilibrium, referred to in other models such as Brunsden and Thornes (1979) as metastable conditions (shown in 3.2D), is dominated by boundaries within the system. The concept of thresholds within the system is fundamental to understanding system change and complex response and questions the idea of persistent, stable landforms occurring as a result of constant process.

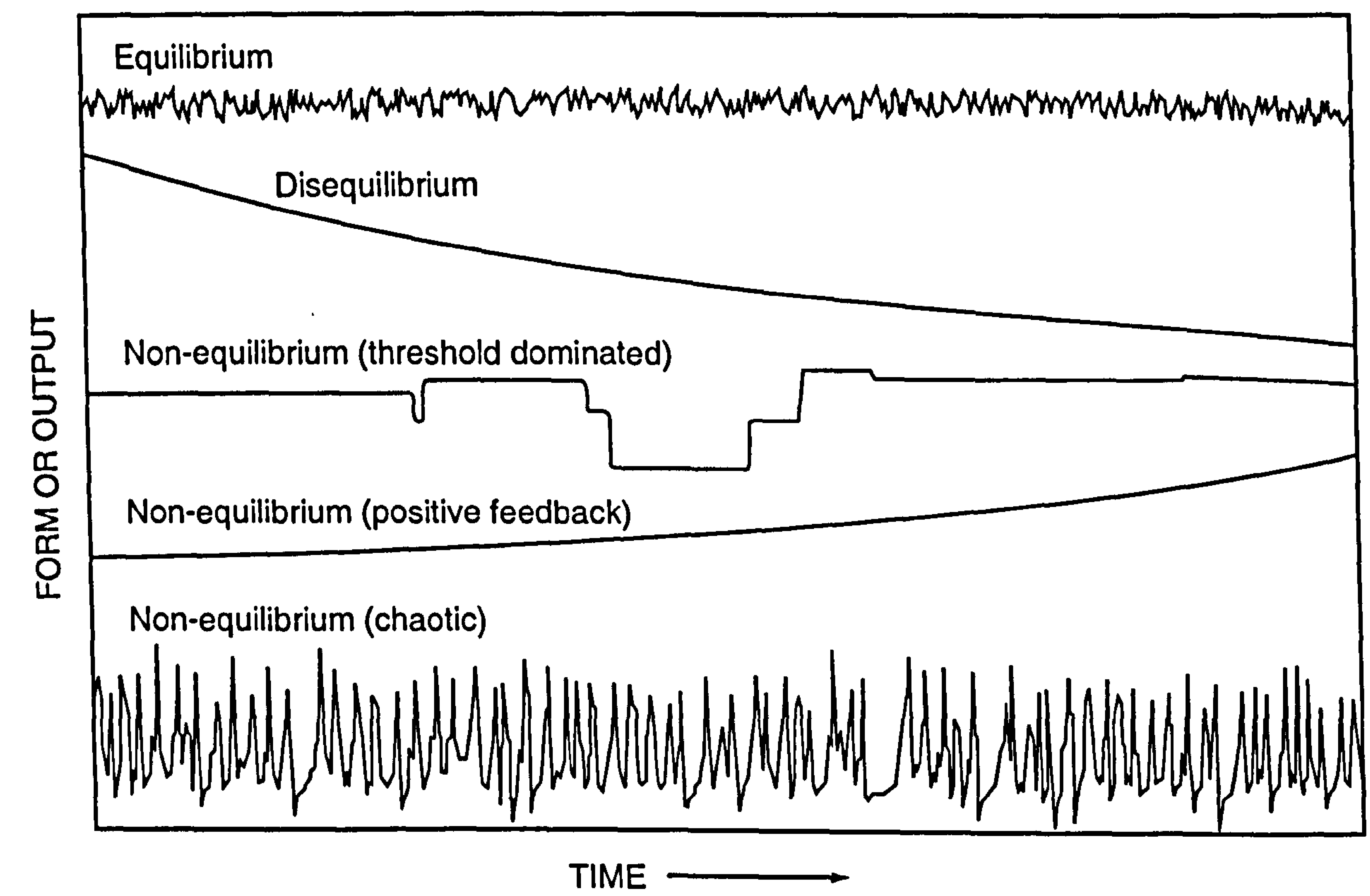


Figure 3.3 Examples of equilibrium, disequilibirum and non-equilibrium, after Renwick (1992) (Knighton, 1998, p.162)

3.3.2 Thresholds and complex response

Schumm (1973) stated that if land systems are in dynamic equilibrium components of the system should respond in the same way to similar external influences. The idea of complex response has developed because this is not the case and landform instability, denoted by geomorphic anomalies, is in fact an inherent part of the erosional system. The number of controlling factors operating within the fluvial system means that change in one or more variable will not always elicit the same response. This is coupled with the idea that change is not always caused by external forces and that behaviour of the system may be controlled by internal disruptions. Transitions within the systems are known as thresholds.

Schumm (1973) defined two types of thresholds, known as extrinsic and intrinsic thresholds, that when crossed trigger abrupt changes or failure within the system. The response of the system to an external force is referred to as an extrinsic threshold. The threshold exists within the system, but it will not be crossed and change will not occur without the influence of an external variable. External shocks to the system may be thought of as pulsed or ramped change (Brunsden and Thornes, 1979). The change imposed is short in relation to the timescale being considered and is followed by a return to the initial state of the system as the effect is spatially as well as temporally restricted. Pulsed change is usually described as an extreme episodic event. Ramped changes are those that are sustained at a new level as a result of permanent shifts in the controlling variables or boundary conditions. This may cause a shift from one process domain to another and result in a response throughout the whole area. The role of extreme events and their effect on the fluvial system must not be overlooked (Brunsden and Thornes, 1979).

The second type of threshold described by Schumm (1973) is known as intrinsic and is exceeded when the input remains relatively constant, yet a progressive change in the system renders it unstable and failure occurs. An example used by Schumm (1973) of an intrinsic threshold of this type is Hjulstrom's (1935) curve showing the velocity required for entrainment and transport of sediment of a given size. The curve shows that critical velocity decreases with sediment size until cohesive forces become significant and then the critical velocity increases with decreasing grain size.

Chappell (1983) refined the working definition of threshold behaviour, making a distinction between transitive and intransitive thresholds. The distinction depends upon whether the new state is persistent (transitive) or short-lived (intransitive). The concept of thresholds and its application to fluvial geomorphology was reviewed by Newson (1992b) in the context of climate change. The need to predict "where and when" rivers will respond to both extrinsic and intrinsic changes highlighted by Newson (1992b) has been approached using threshold theory, but the precise scope and definition of thresholds in geomorphology has been increasingly debated (Newson, 1992b). The question of whether thresholds involve abrupt or gradational change has been the subject of vigorous debate (Werrity, 1997) in terms of transitional planforms and thresholds of transport (Ferguson, 1987; Carson and Griffiths, 1987; Newson, 1992b). There are several key points that can be made with reference to the discussion on threshold theory applied to river channels. First, the need to investigate at the process level because many boundaries within the fluvial system recognised by geomorphological form may not actually represent thresholds (Chappell, 1983). Secondly, the need to address the issue of scale both spatially and temporally to assess whether thresholds exist, how and over what timescales (transitive or intransitive). Finally, with particular reference to this research, the importance of controlling factors on river channel behaviour, both at a reach and downstream needs investigation.

Within a complex system one event can trigger a complex reaction (morphologic or stratigraphic) as the components of the system respond progressively to change (Schumm, 1973). The externally imposed change may diffuse through the system in a manner that is temporally and spatially variable. The behaviour of such a system is indeterminate so that it is not always possible to predict the resulting output patterns from change in input. The principle of complex response provides an explanation of the alluvial complexities and suggests that an infrequent event may in fact, be the catalyst that causes the crossing of a geomorphic threshold and triggering of a complex sequence of events that will produce significant landform modification (Schumm, 1973).

3.3.3 Identification of stability in semi-natural river channels

The concept of stability in this research is based on Renwick's (1992) definition of equilibrium. Although not a static state, equilibrium, is indicated by a relatively stable geomorphic form. The tendency towards equilibrium or stability expresses itself in rivers in the erosional or depositional adjustments of both the longitudinal and the cross-sectional channel profile (Ahnert, 1994). Similar to Gilbert's concept of grade, enlargement of the channel through erosion or the reduction of channel through deposition is indicative of instability within the channel. Stability is attained when there is a balance between form and process and the channel cross-section is not adjusting its cross-section. Several methods have been used to assess river channel stability;

continuous monitoring of channel adjustment; the use of historical maps and field reconnaissance; or geomorphological surveys.

Monitoring is based on continuous records of fluvial processes and forms through time, the ideal data for quantifying past and present channel adjustments. Much of the work on rates of change require monitoring of erosion or deposition (Hooke, 1997), but continuous monitoring over long time periods is often operationally difficult in terms of the cost and practicalities involved with maintaining monitoring stations. There is no UK network of geomorphological gauging stations, and the cost of installing stations and the inherent difficulties of maintenance and use of data (Downs and Thorne, 1996) mean the amount of long-term monitoring in the UK will continue to be restricted.

The use of large-scale historical maps, aerial photographs or remotely sensed images are also useful for observing river channel changes. For example, for the purposes of conservation on the River Feshie, Werrity and Brazier (1992) undertook mapping procedures based on aerial photographs and old maps to try to build up an understanding of the behaviour of the braided channel over the last 250 years. Constituent units of the fluvial system (active channels, abandoned channels, bars and stable zones) were then identified to differentiate between stable and unstable states with lateral channel migration and avulsion. The use of maps and archive information of river channels can be extremely useful, but is often limited in extent and dependent on accuracy and consistency with which the channel is defined.

The long periods between updating and re-issuing of maps may obscure potentially important information, especially during the last 30 years when channel response to human impacts may have been particularly widespread (Downs and Thorne, 1996). The most useful information provided by maps is in terms of planform adjustment, but in most rivers, the instream and vertical adjustments are critical to the identification of significant morphological change.

While historical records of types, trends and rates of channel changes are useful as a basis for determination of the current situation such information is not always available. Even if it is, ongoing changes in catchment characteristics, alterations to channel management, or complexity in the response of the fluvial systems often means that past changes are not representative of current or future adjustments (Downs and Thorne, 1996). This requires the use of field reconnaissance using geomorphological surveys, the most important method for assessing river channel stability and sensitivity to change in river engineering and management (Downs and Thorne, 1996). It is increasingly used within the EA and external engineering companies and consultancies, linked with academic organisations, for specific restoration and management projects, for example, the Mimmshall Brook project (Sear *et al.*, 1994).

Geomorphological surveys or river channel reconnaissance involve the collection of detailed information about the river channel and surrounding catchment during a field investigation (Downs and Thorne, 1996). The information is collected for a single site or several sites downstream using a checklist format (for example, Thorne, 1993). The surveys provide data on channel morphology, in-channel and sedimentary features and aquatic and riparian vegetation, all of which can be used to support inferences of lateral and vertical channel adjustments, also recorded during the survey. The advantage of the geomorphological survey is that it can be tailored to the purpose of the work and provides a means of rapid acquisition of data. It is crucial that the aims of the research are clearly established so that the data collected can be usefully applied.

Geomorphological surveys are usually split into two parts to record information about the *condition* of the river channel (section 3.1) referred to by Thorne et al. (1996) as the management status; and the *state* of the channel (section 3.2) or stability status. The condition of the channel can be classified using terminology outlined in table 3.2 according to the degree of naturalness. The state of the channel can be evaluated by using indicators of river channel adjustment.

The use of field indicators to assess channel morphology was pioneered by Kellerhals *et al.*(1976) in a scheme to assess the nature of Canadian river valleys and the method has since been used by many researchers (Lewin *et al.* 1988; Simon et al, 1989; Thorne 1992; 1993) to evaluate channel morphology. River channel stability can also be assessed on the basis of field indicators (Downs, 1992; 1995 a,b) and the method was tested for consistency by Gregory, Davis and Downs (1992) on the Monks Brook. The channel was surveyed and mapped by the authors independently, using a checklist of vegetation, morphological and structural indicators (table 3.4) that could locate areas of river channel adjustment.

Table 3.4: Field observed indicators of channel adjustment in river channels: developed for lowland channels (Gregory, Davis and Downs, 1992).

Form of Indication	Type	Indicators
Morphological	1	bank erosion by undercutting/slumping/desiccation
	1	exposure of fresh materials in lower bank
	1	evidence of cutoff/ chutes and associated features
	2a	erosion of central channel to form compound cross-section
	2a	tributary bed level higher than main channel
	2a	accretion of continuous low bench
	2b	'fresh' gravels - concentrated at riffle locations or over whole bed
	2b	formation of step/pool sequence
	2b	accretion of point bar
	2b	silt deposition across whole bed
Vegetation	1	exposed tree roots
	1	undercut tree roots/turf root mat
	1	deformed tree
	1	protruding tree (erosion behind)
	1	trees in channel - bed or bench level
	2b	encroachment of (non seasonal) vegetation onto channel bed or bench
	2b	complete cover of bed by seasonal vegetation - exceeding riffle length
Structural	1	erosion behind/under bank protection (leading to damage collapse)
	1	structure protruding into channel
	1	structure set back from current channel bank
	1	erosion immediately downstream of structure
	2a	structure base not at original height relative to channel bed-level

The river was divided into sections according to the homogeneity of morphological adjustment and a checklist morphological survey was carried out for each reach. The results showed a high degree of agreement and 95% of the channel length surveyed separately produced the same results. After the method was tested, the technique was employed to estimate channel adjustments in four rivers in the Thames basin (Downs, 1995b). The results were categorised according to ten styles of adjustment shown in figure 3.4, which reflect permanent change in the channel system or transient conditions that will respond in time. The activity of channels varies and is described within the ten categories.

Gregory (1992) used vegetation to detect channel enlargement on the Highland Water, New Forest, UK. If a channel is being actively eroded it may have indications of vegetation-free bank surfaces, exposed tree roots, undercut channel banks, trees which are curved and have adjusted as they have been undercut (although there is evidence of tree tilting in response to physical conditions, such as shading, unrelated to bank stability, Phipps, 1974) or even trees growing at a low level within the channel as a consequence of erosion that has taken place (Gregory, 1992).

More specific indicators of river stability/instability were developed by Sear et al (1995) and used in this research (Appendix 3, section 3) to classify the river on the basis of Schumm's (1963) classification according to evidence of incision, aggradation or stability defined in table 3.5. If signs of erosion are noted on one bank only, it could be indicative of autogenic change, where the translation of the channel involves bank erosion on one side and deposition on the other and no net change in the channel morphology. However, if features of erosion or aggradation occur on facing sides of the channel, then this may be indicative of allogenic change, where the channel is enlarging or reducing in size and is unstable (Gregory, 1992).

Table 3.5 Classification of river channels according to Schumm (1963)

Classification	*Description*
Eroding	Progressive degradation of the stream bed and/or channel widening due to a deficiency of total sediment load.
Stable	No progressive change in channel form although short-term variations may occur during floods.
Depositing	Progressive aggradation and/or bank deposition due to an excessive load.

Indicators of channel stability are incorporated into *Guidelines for the Design and Restoration of Flood Alleviation Schemes* produced at the University of East Anglia for the Environment Agency (1993). Identification of a channel that is aggrading and degrading and differentiation of areas more sensitive to change indicates when a scheme may be adversely affected by channel instability. This approach has been used in the EA with geomorphological guidance notes produced by the Geodata Institute (1994).

	Stable	Deposition	Lateral Migration	Enlargement
Stable	S			
Deposition	d	D		
Lateral Migration	m	R	M	
Enlargement	e	C	U	E

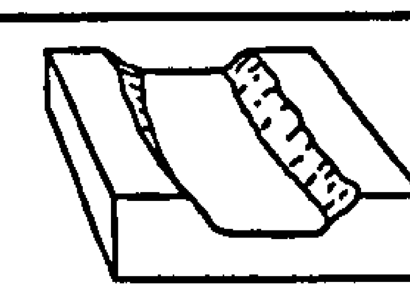
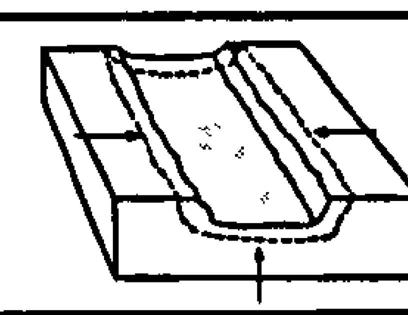
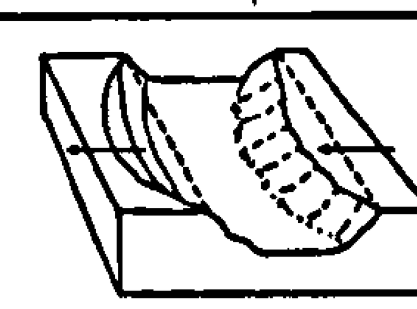
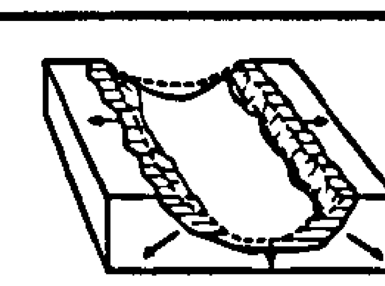
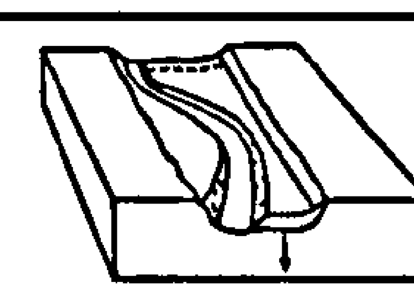
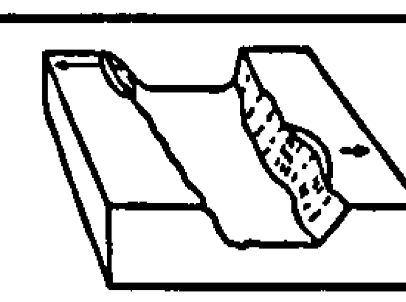
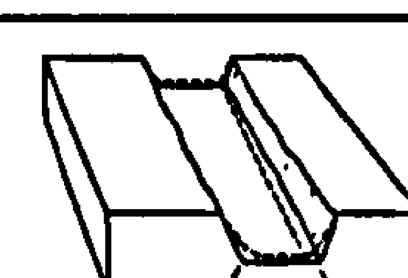
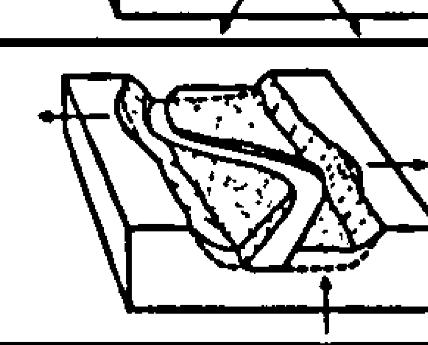
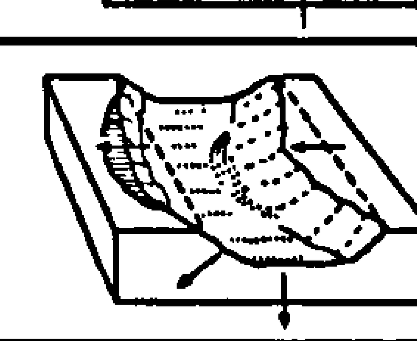
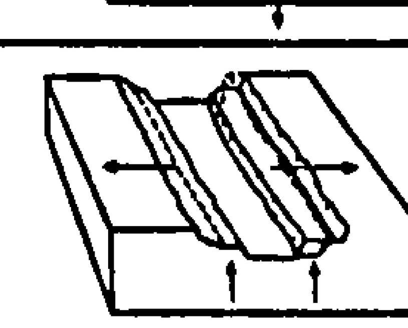
Channel condition	Description	Definition
S	no morphological activity	
D	deposition on both banks and bed	
M	migration of most bends	
E	enlargement of both banks and bed	
d	less intense deposition	
m	less intense migration	
e	less intense enlargement	
R	migration and deposition	
U	enlargement and migration	
C	enlargement and deposition	

Figure 3.4 **Ten styles of river channel adjustment defined by Downs (1995b)**

Hydraulics Research (1992) classified river channel stability according to unstable and stable, making a distinction between stable (dynamic) and stable (moribund) a function of a river's ability to alter its channel either naturally or in response to an externally imposed change (Thorne et al, 1996). A dynamically stable channel is a self formed channel where the characteristic dimensions and features of the channel do not change over short time-scales. Moribund channels refer to channels which have not been formed by the present flow regime and are legacy of past processes, characterised by low gradients and energy levels coupled with erosion resistant bed and bank materials. They display very stable forms and features and do not have enough energy to recover from major engineering works (Thorne *et al*, 1996).

Downs and Thorne (1996) highlighted the importance of geomorphological surveys in river management and presented a geomorphological justification for their use in pre-project planning of restoration and flood alleviation schemes and for conservation. However, Thorne (1997) stressed the importance of careful observation coupled with insight into process-form linkages, when inferring adjustment processes from indicators of channel form. The interpretation of morphological data requires reliable and repeatable methods of stream reconnaissance and sound judgement.

Thorne *et al.* (1996) suggest that a role for more objective, quantitative analysis in supporting and validating the findings of the qualitative survey, remains as a complementary component of geomorphological analysis. The interpretation of the quantitative phase of river reconnaissance using residual values from channel geometry - discharge relations is suggested as a method of assessing river channel stability.

3.3.4 The potential use of residual values for the assessment of river channel stability

The variability of channel geometry - discharge relations shown by the residual values indicating the difference between the observed values of river channel dimensions and the values predicted by the regression model was discussed in Chapter 2 (section 2.8). Stability is based on the relationship between channel form and the discharge that controls the transport of sediment and thus the rate of erosion and deposition. The downstream hydraulic geometry model is based on the line of best fit through the data that produces an average relationship between channel dimensions and width. For a wide-ranging dataset the difference between the observed values and predicted values may be a measure of the state of the channel or broadly indicative of the direction of change. For example, positive residuals that indicate that channels that are over-wide in relation to the model (figure 3.5), may be adjusting towards the model line by reducing channel width through deposition. Conversely, negative residuals, under-wide channels in relation to the model, may be enlarging to adjust towards equilibrium.

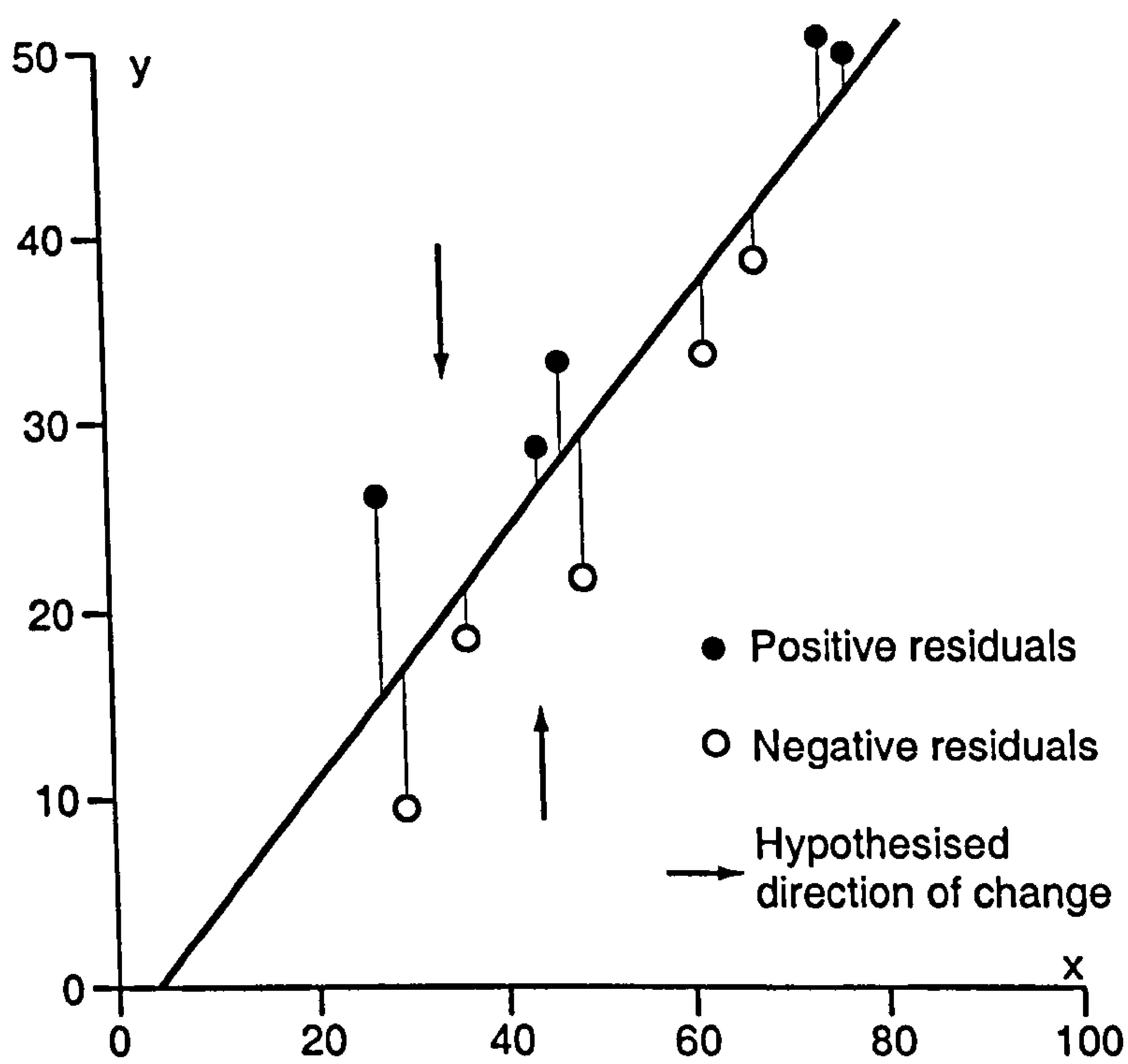


Figure 3.5 **Plot of residuals showing the hypothesised direction of change**

Schumm (1960) was the first to look at the shape of alluvial channels in relation to sediment type to assess whether channels were aggrading or degrading. A regression analysis was carried out on 21 rivers from a database of ninety cross-sections in the USA. Those channels which show scour are found lying far below the regression line of best fit, whereas those points lying above the line show a progressive increase in gauge height with consistent discharge suggesting aggradation. Schumm (1960) suggests that the relation of the points to the regression line may be used as a criterion of channel stability. The channel cross-sections that plot above the line because they have been aggraded or are aggrading, may be expected to regress towards a stable form by erosion; whereas channel cross-sections that plot below the line because they are degrading or have been degraded, maybe expected to regress towards a stable form by a combination of bank erosion and aggradation.

The geomorphological significance of residual values was discussed in work by Wharton (1989) where channel geometry - discharge relations were developed from UK data to estimate flood discharges from channel dimensions. It was suggested that the sign of the residual value could indicate the likely direction of change towards an average channel - geometry discharge relationship (figure 3.6). The magnitude of the residual value might provide a measure of the sensitivity of the channel to change, in that a large percentage residual value reflects a large local deviation and may indicate a greater instability and an increased likelihood of channel change (Wharton, 1989; 1992). The failure of channels to comply with appropriate hydraulic geometry relationships was also proposed as one diagnostic for stability by Johnson and Neill (1990).

Thorne *et al.* (1996) propose the use of residuals for different channel parameters to assess river channel adjustment, for example, if the width is close to the model line it is important to assess depth, cross-sectional area and form ratio to evaluate whether the channel is incised or not. Depending on the regional stability of the system identified from quantitative analysis of adjacent reaches plus wider, quantitative analysis of the system an understanding of adjustment can be built up (Thorne *et al.*, 1996). It is important to consider all the limitations of regression analysis and hydraulic geometry when assessing variability of residual values, as discussed in Chapter 2. More research needs to be done on the validity of using residual values and their geomorhpological implications and this research focuses upon this issue.

3.4 Sensitivity to change

The question of sensitivity focuses on the potential and likely magnitude of change within a physical system and the ability of the system to resist change (Allison and Thomas, 1993). The application of fluvial geomorphology to river management and restoration has highlighted the need for a clear understanding of the sensitivity of river channels to change at different temporal scales (Thorne, Hey and Newson, 1997). In a recent investigation of the sensitivity of river channels in the landscape system, Downs and Gregory (1993; 1995), noted that there had been comparatively few explicit reviews of sensitivity in relation to river channels despite a wide variety of approaches to geomorphic sensitivity. One of the main problems is that there is no consistent method for the investigation of sensitivity, explained by the gap between conceptual understanding of geomorphological systems and the data available to analyse them.

3.4.1 Approaches to river channel sensitivity

Downs and Gregory (1995) suggested that definitions of geomorphological sensitivity should be arranged according to four hierarchical definitions of investigation related to data demands (Figure 3.6).

INTERPRETATION OF SENSITIVTY	UNITS	EXAMPLES OF RIVER CHANNEL REPSONSE Magnitude of force imbalance Contraction/ Aggradation — Equilibrium — Enlargement/ Degradation	EXAMPLE OF EXPRESSION IN FLUVIAL SYSTEM	APPLICATION TO ENVIRONMENTAL MANAGEMENT
1. Ratio of disturbing to resisting forces	Dimensionless	or	Channel change if disturbing force, eg storm event, exceeds resistance of channel parameter	Use of energetics to relate river channel to other physical systems (eg Gregory, 1987b)
2. Proximity to thresholds in relation to the imbalance of forces	Force	Threshold Threshold	Proximity to single-thread/multi-thread threshold	Proximity to threshold can be used to indicate sensitivity of individual areas (eg Graf, 1981)
3. Ability for recovery from change in the balance of forces	Time for recovery OR Dimensionless if ratio of recurrence interval : relaxation time	---- actual sequence of changes	Recovery from impact of flood event or platform recovery following channel straightening	Resiliance of system to recovery after a major flood (eg Gupta and Fox, 1974)
4. Time dependent rate of system response as revealed by sensitivity analysis	Quantity morphological change per unit parameter alteration	Time; unit parameter alteration	Extent to which some aspect of short-term fluvial system behaviour conforms to longer-term trend	Understanding of the singular nature of individual locations within fluvial systems (eg as an extension of the model developed for river channel changes downstream of dams by Williams and Wolman, 1984)

Figure 3.6 Connotations and examples for the four interpretations of river channel sensitivity (Downs and Gregory, 1995, p. 17).

The ratio of disturbing forces to resisting forces can be viewed in terms of the potential energy within the system (Brunsden and Thornes, 1979). The geomorphic system is described using the example of energy required to move particles on the river bed (figure 3.5). Particles in the headwaters of the fluvial system (particle A, figure 3.5) have a greater propensity for movement, compared with those further downstream (particle B) because there is greater potential energy. The ratio of disturbing forces (potential energy within the system) to resisting forces is also dependent on the local characteristics. Thus, for disturbing forces of the same magnitude, the response of a channel with resistant channel banks will differ from a channel with erodible banks, which is more susceptible to bank erosion and width increases. This is the simplest and most frequently used interpretation of sensitivity (Downs and Gregory, 1995).

The second interpretation of sensitivity centres on the forces necessary to reach and exceed critical thresholds within the system (Downs and Gregory, 1995). Irrespective of the type of disturbance involved, the response ultimately depends on the nature of the geomorphic system and its limiting thresholds (Werrity, 1997). The proximity of the system to thresholds represents the sensitivity of the system to change. This is shown in Figure 3.5 in which each particle is surrounded by barriers to change. The movement of the particle across these barriers depends on the distribution of forces, for example, particle C is more sensitive to change compared with particle B, because it is closer to the threshold of change. As discussed in section 3.2.2, the type of threshold and the length of time that change persists for is important in determining landform response. Werrity and Brazier (1994) described landforms as *robust* or *responsive* (table 3.6) according to limiting thresholds operating within the system.

Table 3.6 Definitions of robust and responsive landforms

Term	*Definition*
Robust landforms	'robust landforms retain a stable identity as they form and reform, under a given process regime, despite being changed as intrinsic thresholds are crossed' (Werrity and Brazier, 1994, p.103)
Responsive landforms	'responsive landforms are those which, in response to externally imposed change, cross extrinsic thresholds to reproduce a new assemblage of landforms' (Werrity, 1997, p.48)

Some high energy fluvial systems (such as active, braided channels) are subject to frequent change by processes which occur many times over short time-scales and involve the crossing of intrinsic thresholds. The processes are an inherent part of the system and despite changes to landforms on the valley floor, the landform is robust maintaining a recognisable form (Werrity, 1997). If, however, the imposed disturbance causes the system to cross an extrinsic threshold into a new process regime in which a very different assemblage of landforms is likely to develop, then the initial landform assemblage is responsive to change. The proximity of river channels to thresholds of change was advocated by Downs and Gregory (1995) as perhaps the most valuable, but the issues surrounding thresholds discussed in section 3.2.2 must be borne in mind.

Attention must be paid to the ability of the system to absorb and store energy and mass, thereby reducing the effects of any impulse of change (interpretation 3). Once change has been initiated, the rate of absorption determines the time of attainment of a new characteristic form. These are known as rate laws and describe the temporal variability of sensitivity within the system. There are three aspects of system behaviour in the transition from one equilibrium state to another, a reaction time, a relaxation period and a characteristic path for change (Brunsden, 1980).

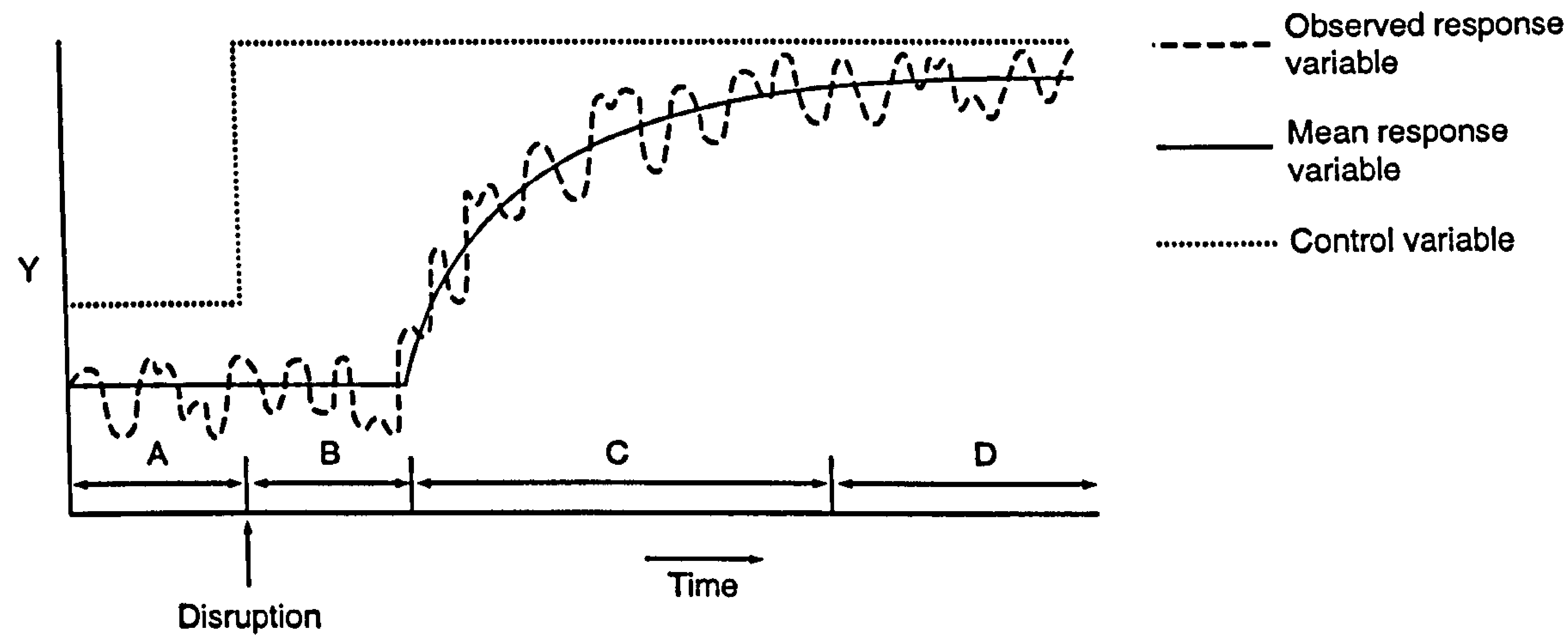


Figure 3.7 Example of system change between two states of equilibrium. The vertical axis represents the value of a typical system such as stream width. The horizontal axis represents time. A and D are equilibrium states, B is reaction time, C is relaxation time (modified from Graf 1988, p. 41)

The reaction time is the time taken for a system to react to changes in conditions, shown as B in figure 3.7. The time it takes between the beginning of change and the establishment of the new equilibrium state is known as the relaxation time (Melton, 1958). The relaxation time is an indicator of the responsiveness of a system to imposed changes and if it can be defined, accurate predictions of the time to stability might be possible (Graf, 1988). When the system has reached a new stability the system is again in equilibrium, although it is often impossible for a river channel to reach this state as a new impulse of change may affect the channel before it has stabilised.

Much sensitivity work taking this approach, concerns the recovery of landforms from high magnitude low frequency events expressed by a ratio of recurrence interval to recovery time (Wolman and Gerson, 1978). Recovery time is that required for an erosional feature, produced by an isolated pulse, to be obliterated or returned to its original form, for example, Downs and Gregory (1995). Landforms with high recovery rates may be expected to exhibit considerable temporal adjustment to the general magnitude of frequent processes, whereas those of low recovery usually show the effects of infrequent high intensity events (Chorley *et al.,* 1984). The time variable has been added to this interpretation of sensitivity and as a result the data requirements are significantly increased and the importance of longer term temporal records are important.

The final interpretation of sensitivity is based on a deterministic understanding of river system behaviour. If deterministic modelling was possible on a large scale, the response would be reported in terms of the quantity of morphological change per unit input parameter alteration, for example, unit increase of width for unit increase of discharge.

In hydrological modelling, sensitivity describes a precise function. This function is derived from the optimisation of a deterministic mathematical model and produces an index (normal/relative) that describes how the output of the model varies in relation to variation in the factors contained within the model. The main problem with applying this technique to geomorphology is response indeterminacy (Anderson and Sambles, 1988). Lack of practical modelling in geomorphology was seen in the late 1980's to reflect uncertainties concerning model assumptions, the influence of high magnitude, low frequency events, the difficulty of documenting the output of the model and the fact that geomorphological models are likely to be unique to the time-base for which the model is constructed (Anderson and Sambles, 1988). Most hydraulic models contain a basic assumption of equilibrium, but for some river channels equilibrium is never achieved and the channel is characterised by inherent instability (particularly in semi arid regions), for example the Gila River, Arizona USA (Graf, 1981). During the 1990's, there has been a shift in geomorphological research from the study and explanation of equilibrium channel forms to investigations designed to support an improved understanding of dynamic process-response mechanisms, in non-equilibrium channels (Downs and Thorne, 1996). Despite an improved qualitative understanding and explanation, the equations and algorithms necessary to allow morphological adjustments of channels with mobile bed and banks, to be modelled numerically are not yet developed. The amounts of data required for input into the model are again a limiting factor and the extrapolation of historical records is only beneficial where stationarity of the controlling variables or a continuation of current rates of change can be assumed.

Progress has been made at the small-scale with work by Osman and Thorne (1988a,b) and Simon *et al.* (1991) leading to the development of physically - based bank failure algorithms. These were coupled with hydraulic and sediment transport routines to produce a channel evolution model constructed by Darby (1994) that accounts for vertical and lateral adjustments in channel shape. The capability to perform process-based modelling of geomorphological change is highly desirable for river channel management purposes because it facilitates prediction of channel response to changes in external variables. Applicability is limited at present to one dimensional modelling of straight channels (Darby, 1994) which precludes most practical applications (Downs and Thorne, 1996).

3.4.2 The importance of scale in the assessment of river sensitivity to change

Assessing river channel sensitivity, requires geomorphological interpretation from the field data at different spatial and temporal scales. River channel adjustment can be complex in spatial and temporal terms. Hooke (1997) argues that the assumption of attainment and stability of equilibrium forms over short time-scales must be questioned as the evidence grows of continued patterns of evolution over centuries rather than adjustments in decades. The time-scales used to assess river sensitivity are therefore important as short-term adjustments may be obscuring longer term tendencies towards equilibrium (Richards and Lane, 1997). The ability of the system to absorb impulses of change is important in determining the time taken for a river to adjust to a new stable form. The constant fluctuation of conditions may mean that for responsive systems that are sensitive to change, it may take many years before stability is achieved and it is questionable whether stability can ever be fully attained. For management purposes, it is necessary to consider how channels will change in the short-term (10-20 years), even though longer term patterns of change may be underlying.

It is also important to consider how sensitivity varies at different spatial scales and at what time-scales. The link between temporal and spatial scales was first recognised by Schumm and Lichty (1965) who found that slow processes are likely to manifest at the larger spatial scales over longer periods of observation. Over shorter time periods and limited spatial scales, these slow processes are inseparable from the noise of the system.

Frissell et al (1986) developed the idea that the sensitivity and recovery time of river habitats change at different spatial scales, based on the ideas of hierarchy (Allen and Starr, 1982). This concept can also be applied to geomorphology. It is based on the idea that events that affect smaller-scale habitats may not affect larger scale system characteristics whereas larger disturbances can directly influence smaller scale features of the stream. For example, on a small spatial scale, deposition at the habitat scale caused by small scale adjustments in the flow may be accompanied by scouring at another site nearby and the reach or segment does not appear to change significantly. In contrast, large scale disturbance, perhaps initiated at the segment level, is transferred to all smaller scales.

The scale of controlling factors is therefore important and changes at the reach scale must be viewed in the context of the catchment, an idea reflected in the channel morphometry approach. At a large spatial scale, the catchment, a discrete geographical area with boundaries defined by topographical and hydrological limits, operates as a complex environmental system. Within this system, the extent to which sections of river are *integrated*, behaving similarly to changes in controlling factors, or *fragmented*, exhibiting spatially-varied response (Beyer, 1997) is fundamental to understanding river channel change. Channel instability may be localised, involve long reaches or even affect an entire fluvial system. The spatial extent and magnitude of instability provides evidence on the cause or causes of that instability (Thorne *et al.*, 1996) and whether local or basin wide factors are causing instability. The use of GIS-based systems of screening are advocated by Thorne *et al.*, (1996).

Sub-division of the catchment into segments was first used in geomorphology by Gilbert in 1877 who suggested that region slope units are connected together in an integrated series of input and output sub-systems. When a given segment of slope erodes, it contributes material to the next segment downslope but it also receives material coming down from the next segment above. Changes are therefore propagated through the system. Schumm (1973) applied this theory to stream systems where segments of the channel are connected and no single reach can be thought of in isolation. If a threshold is exceeded and a process change occurs in one part of the system, the effects may eventually extend throughout the river system (Graf, 1988). The reach is influenced by *longitudinal* controls, changes downstream though the catchment. There has been recent recognition of this connectivity by Newson (1992a) who termed this new strategic thinking as "extensification".

Sensitivity is therefore dependent on small scale factors controlling stability but on the sensitivity of the whole system. Conservation and management issues are underpinned by the need to consider stability and sensitivity, not only of the river but the catchment in relation to the reach in question. The causes of river maintenance problems, although manifested in the channel through erosion and deposition at a single reach are often catchment wide and the reach must therefore be considered in relation to the catchment. This has been further highlighted by the development of river restoration, that has shown that in the case of the Mimmshall Brook, Hertfordshire, England (Sear *et al.* 1994), the failure to account for linkages between the catchment and upstream/downstream stability may ultimately lead to the failure of design.

3.5 Summary

The assessment of river channel stability for the prediction of river channel sensitivity to change is increasingly recognised as fundamental to sustainable river engineering and management. The selection of management strategies, restoration measures and, in the case of specific problems, engineering solutions, require an appraisal of the present morphological features and fluvial processes in the project reach and a prediction of future features and processes (Newson, 1992a). This chapter has highlighted the importance of assessing the condition and state of a river at different spatial scales. The condition (management status) of the river channel refers to the degree of naturalness; the state of the channel refers to river channel stability (stability status) and both factors determine the sensitivity of the channel to change. Methods of assessing river channel stability were discussed and the use of residuals from channel geometry - discharge relationships as geomorphological indicators was outlined as the basis of study for this research. Chapter 4 will discuss the research and results for the national study followed by the catchment study in Chapter 5.

CHAPTER 4

THE NATIONAL STUDY

4.1 Introduction

The aim of the national study is to investigate the significance of residual values from channel geometry-discharge relations, as indicators of river channel stability and sensitivity to change, over a wide range of environmental conditions. The research will focus on the variability of downstream channel geometry - discharge relations between rivers, to investigate the extent to which residual values can be used to indicate channel form and behaviour and to evaluate the controls on channel-geometry and river channel adjustment. To achieve this aim, three main research objectives are identified shown in table 4.1.

Table 4.1 Research Objectives for the National Study

- To determine whether the residual values from channel geometry-discharge relation are representative of rivers with similar size and discharge.
- To assess the extent to which the residual values are representative of stability and identify the dominant factors in addition to discharge influencing channel behaviour.
- To investigate short-term temporal changes in channel geometry and whether they are consistent with the hypothesised direction of change.

4.2 Experimental Design

The experimental design is structured according to these three objectives. The research framework, shown in figure 4.1, progresses through three stages, commencing with the development of the national model based on a regression model of bankfull width and discharge data from 124 UK river sites. The residuals derived from the national model form the basis of this research. The dataset was divided according to residual magnitude and direction and preliminary analysis was undertaken to assess whether the residual values were representative of rivers with similar cross-sectional forms or flow magnitudes.

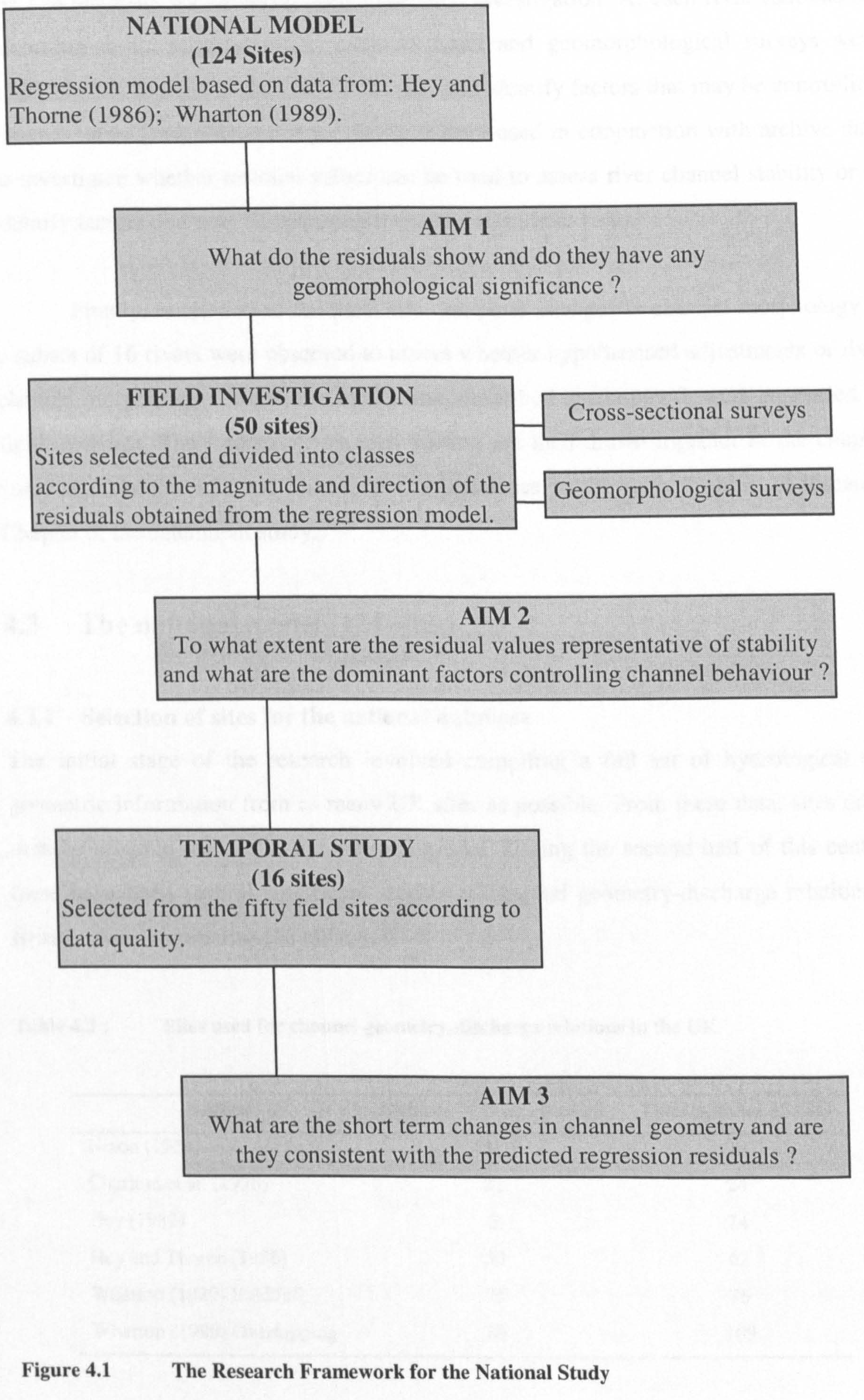


Figure 4.1 **The Research Framework for the National Study**

On the basis of the findings from the initial analysis, a subset of fifty sites from the 124 residuals was selected for further field investigation. At each river site, chosen according to its residual value, cross-sectional and geomorphological surveys were undertaken to assess the state of the channel and identify factors that may be controlling channel form. Data obtained from the field were used in conjunction with archive data to investigate whether residual values can be used to assess river channel stability or to identify factors that may be operating to control river behaviour.

Finally, in relation to the third aim, temporal changes in channel morphology in a subset of 16 rivers were observed to assess whether hypothesised adjustments of river channel morphology towards the model line, described in Chapter 3, were supported by field evidence. The findings from each section are then drawn together in the chapter summary (section 4.5) and discussed with reference to the second phase of research, Chapter 5, the catchment study.

4.3 The national model (124 sites)

4.3.1 Selection of sites for the national database

The initial stage of the research involved compiling a full set of hydrological and geometric information from as many UK sites as possible. From these data, sites could then be selected for use in the national model. During the second half of this century there have been several significant studies of channel geometry-discharge relations in British rivers summarised in table 4.2.

Table 4.2 : Sites used for channel geometry-discharge relations in the UK

Author	Number of rivers studied	Total number of sites
Nixon (1959)	22	29
Charlton et al. (1978)	22	24
Hey (1982)	3	74
Hey and Thorne (1986)	53	62
Wharton (1989) Bankfull	75	75
Wharton (1989) Overtopping	86	109

After detailed investigation, it was decided that only sites used by Hey and Thorne (1986) and bankfull sites from Wharton (1989) should be included for use in the national model. This was for several reasons. Firstly, the data from Hey and Thorne (1986) and Wharton (1989) were measured relatively recently increasing the likelihood that the sites would still be in a suitable condition for use in this research. Secondly, both datasets were accompanied by detailed information about how the sites were selected and the criteria used to identify the reach to be measured at each site, information lacking in the other sources. Finally, similar field methods were used by Hey and Thorne (1986) and Wharton (1989), essential in terms of consistency.

Wharton's (1989) dataset was divided into bankfull and overtopping sites (see section 4.5.3, figure 4.11) based on data from three separate sources: Surface Water Archive data (SWAD), Additional Archive data (AAD) and Field Survey data (FSD) with some overlap resulting in several sites appearing in more than one data set. The archive data (SWAD and AAD) obtained from the Institute of Hydrology, used the overtopping level as the reference level for the measurement of channel dimensions. The Field Survey data were obtained from field measurements carried out during 1987 and 1988 using the active bankfull level. For the purposes of this research, only the Field Survey Data measured to the bankfull level were selected for use in the regression model to reduce the amount of variability due to measurement error. This research focuses on the significance of residual values and it was essential to keep any artificial sources of error, which could affect residual magnitude, to a minimum. To ensure the quality of both hydrometric and geometric data, both Wharton (1989) and Hey and Thorne (1986) employed strict criteria for the selection of sites based on the quality of the flow data, and the condition and state of the site.

The FSD sites used by Wharton were selected from the Surface Water Archive (Institute of Hydrology, Wallingford), that holds annual maximum and peaks over threshold flood peak data for a total of 917 UK gauging stations. From this archive a subset of 643 annual maximum stations was selected for use in the initial stage of analysis, according to the highest quality stage rating curves. The classification system developed in the *Flood Studies Report* (NERC, 1975) was used to assess the quality of the flow data. Flood rating quality is divided into four grades A-D shown in table 4.3. Sites were selected from categories A and B, the highest quality flow records. It was essential to ensure high quality of both channel geometry and discharge data. Grades C and D imply undue extrapolation with an unacceptable range of error excluding them from use in the development of channel geometry-discharge relations.

Table 4.3 **Criteria for gauging station grades for different types of station (from *Flood Studies Report*, volume IV, 1975, p.6)**

GRADE	RIVER SECTION
A1	Rating well defined by current meter
A2	Rating less well defined
B	Valid extrapolation of a sufficient A grade rating to level where cross-section geometry and flow conditions change
C	Further extrapolation of B grade rating beyond channel conditions characteristic of base rating. Limited to an increase in width equal to main channel width. Upgrade to B if indirect measurements in this range have been made.
D	As for C, but width of flood plain greater than width of main channel. Upgrade to C is indirect measurements have been made in this range.
E	Rejection grade - Low flow rating only; rating relationship not unique owing to tidal influences
Z	Rejection based on other factors than rating - levels only, excessive truncation, persistent malfunction of installation, very short record, reservoir discharge, spring flow.
	N.B. The station grade listed in this report is the grade corresponding to the mean annual flood.

Wharton (1989) also specified that the gauging station should have a minimum flow record of five years. Hey and Thorne (1986) specified that sites should be located immediately adjacent to the flow gauging station which should have a flow record of at least ten years and a consistent, reliable and accurate stage-discharge relationship, especially at high flows or bankfull discharge. A further criterion was that the flow regime should not be severely affected by the operation of reservoirs or inter-basin transfer schemes.

Once the sites had been selected according to the quality of hydrological data, further criteria concerning the condition and state of the river reach (table 4.4) were used during field reconnaissance to guide the final site selection process.

Table 4.4 **Criteria used to select sites according to river channel condition and state**

Hey and Thorne (1986)

- The bed of the river should be formed predominantly in alluvial gravel.
- The river should be a self-formed channel and be free from constraints such as bedrock outcrops or river training structures.
- The river should have a well-defined flood plain.
- The channel should be stable and in natural equilibrium with the flow regime and sediment supply.

Wharton (1989)

- No channelisation affecting the river morphology

There was some overlap between sites used by Hey and Thorne (1986) and Wharton (1989) and sites that had been measured by both authors were only included once in the dataset to avoid repetition that could adversely affect the regression outcome. Where this was the case Wharton's (1989) data were used and the site excluded from Hey and Thorne's dataset, leaving 49 Hey and Thorne (1986) sites to be combined with Wharton's 75 bankfull sites for the final dataset (124 sites) to be used in the regression model.

The geographical distribution of the sites selected is shown in Figure 4.2. It is clear that there are few sites in the East and Central areas of England. This is because of the difficulties of identifying semi-natural reaches located close to gauging stations. Many of the rivers in this area have been channelised for the purposes of drainage and agriculture or have heavily regulated flow regimes. In addition, the problems of accessing the channel to allow cross-sectional measurement imposed a further size constraint on site selection. When considering the variability within the regression model, it must be remembered that the findings apply only to the dataset of 124 sites. The geographical limitations of the dataset must therefore be incorporated into discussions of the research findings.

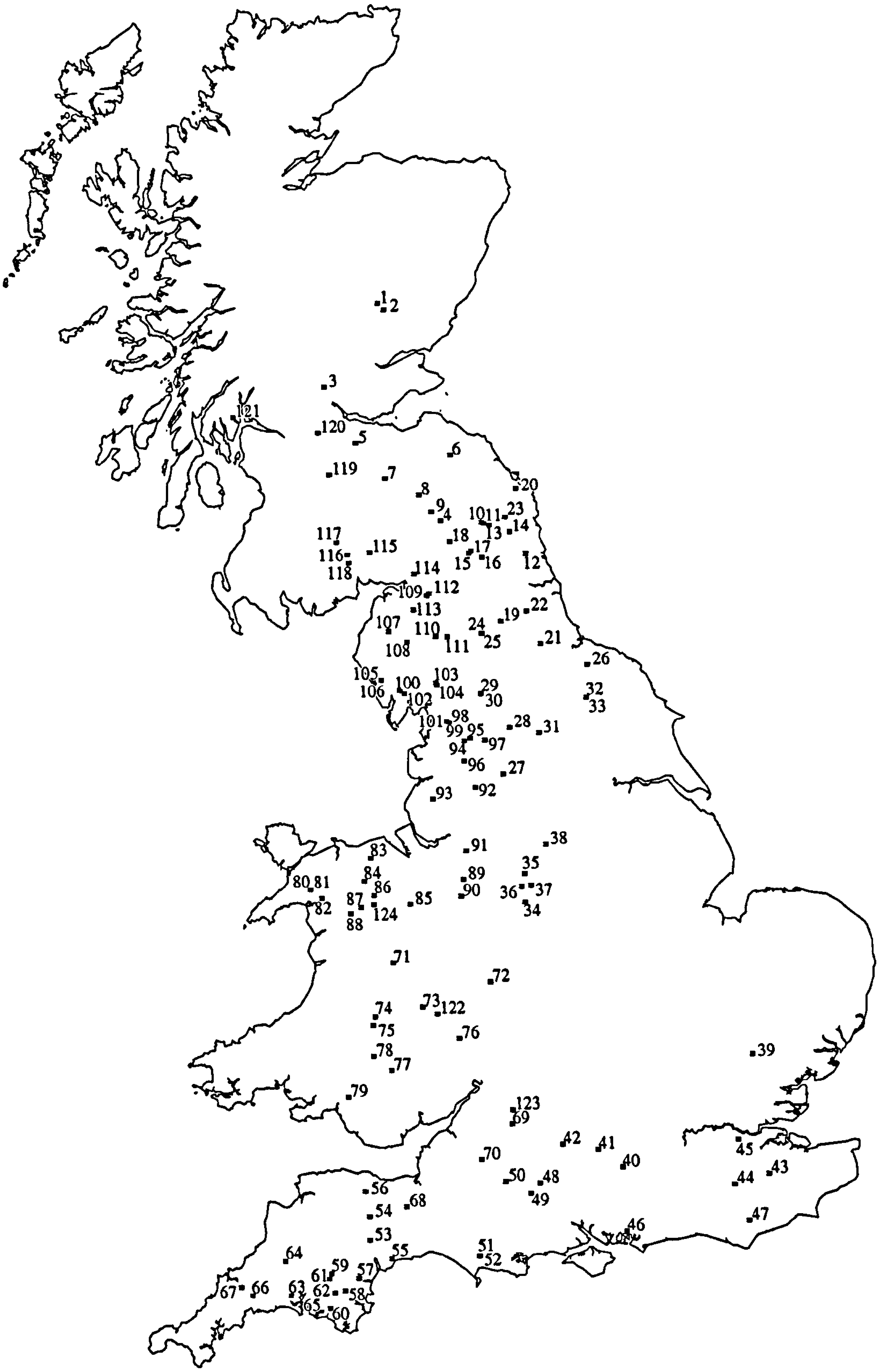


Figure 4.2 The location of the national database of sites

4.3.2 The national dataset

The dataset consists of hydrometric and geometric data obtained by Hey and Throne (1986) and Wharton (1989) for each of the 124 sites (shown in appendix 1 and 2). Channel dimensions were obtained from field measurements using standard surveying techniques. To represent maximum local geomorphological variability at each reach, a minimum of three cross-sectional surveys were measured from which average geometric values were derived. The cross-sections were measured to the bankfull level (active floodplain level, see Chapter 2, table 2.2). Where no active floodplain was identifiable at the reach, a combination of morphological measures such as perennial vegetation, breaks in slope or the grain size boundary were used to identify the active bankfull level. In addition, Hey and Thorne (1986) used the minimum W:D ratio to accurately specify the bankfull level.

The development of channel geometry – discharge relationships are dependent upon the use of a single reference discharge. Despite the limitations of using dominant discharge (described in section 2.4.1) it was necessary for both Hey and Thorne (1986) and Wharton (1989) to select a representative measure channel-forming discharge. Hey and Thorne (1986) used bankfull discharge (Qb m^3s^{-1}) derived from the stage discharge relation for the gauging station, given the stage elevation corresponding to the bankfull flow in the surveyed reach. Wharton (1989) used mean annual flood (Q_{maf} m^3s^{-1}), assumed to equate with the bankfull flow used by Hey and Thorne (1986), calculated from the annual maximum series for each gauging station as an average for the period of record. From henceforth, the term dominant discharge (Qd) refers to either Qb or Q_{maf} according to the source of the data.

4.3.3 The national regression model of 124 UK sites

The national model was developed using simple bi-variate regression analyses between the independent variable, dominant discharge (Qd) and the dependent variables width (w), mean depth (d), maximum depth (dmax), and estimated channel capacity (ESTCA). Regression analysis is based on fitting a linear trendline through the data plot using a least squares procedure to maximise the goodness of fit of the line. To accurately fit the trendline (referred to in this study as the regression line) it is important to ensure that there is a linear relationship between the two variables. This was achieved by expressing both the dependent and independent variables as their base 10 logarithms a frequently used method of transforming the data to produce a linear relationship (Johnston, 1980; Hey and Throne, 1986; Wharton, 1989). Regression analysis was carried out on the basis of the assumptions of linearity, obtained by logarithmically transforming the data, error minimisation in the independent variables, obtained from highest quality gauging station records and normality, verified by checking that the residual values were normally distributed.

The results of regression analyses are shown in table 4.5. The strongest relationships exist between width and Qd (R^2= 0.76; SEE= 0.127), closely followed by estimated channel capacity (R^2= 0.735; SEE= 0.206). In comparison, the depth discharge relationships are less strongly related with lower R^2 and higher SEE values. This is consistent with previous studies of channel-geometry discharge relations discussed in section 2.1.2 which show that width is more strongly correlated with discharge than depth and suggests that the relationship between depth and discharge may be more complex and dependent upon other controlling variables (Richards, 1978; Wharton, 1992; Darby, 1994). The regression coefficient for the depth - discharge regression model is more likely to represent factors such as bank materials and bedload transport, which are hard to quantify and which interact to produce a complex response in channel depth across a single cross-section.

Table 4.5 Results of regression analyses of river channel dimensions with Qd (124 sites)

Dependent variables	b_0	b_1	R^2	SEb_1	t	SEE
Bankfull Width (w)	0.54	0.419	0.760	0.021	19.78	0.127
Max Depth (dmax)	0.30	0.862	0.349	0.105	8.18	0.630
Mean Depth (d)	0.23	0.597	0.372	0.069	8.59	0.415
Estimated Channel Capacity	0.23	0.636	0.735	0.034	18.50	0.206

R^2 is the coefficient of determination; b_1 is the regression coefficient (exponent); b_0 is the intercept of the regression line with the y axis (constant); SEb_1 is the standard error of the regression coefficient; the t value is the regression coefficient (b_1) divided by the standard error of the coefficient (seb_1); SEE is the standard error of the estimate, a measure of variation in the predicted values. Estimated channel capacity (m^3) was calculated by multiplying width (m) and mean depth (m). All channel dimensions were recorded at the bankfull level.

Discharge explains over twice the variation in width ($R^2 = 0.76$) compared with mean depth ($R^2 = 0.372$). It could be argued therefore that variability in width discharge relations may be more significant in terms of stability compared with depth discharge relations, where less of the variability can be explained the model and many other factors in addition to discharge are controlling channel depth. The regression model relating bankfull channel width and Qd, where the influence of discharge was clearest was therefore used to investigate the significance of variability. The equation for the regression line is shown below:

$$\log_{10} W = 0.54 \log_{10} Qd^{0.42} \tag{4.1}$$

4.3.4 Analysis of the residuals: method

The distribution of residual values along the regression line was investigated and the assumption that residuals should be normally distributed along the regression line was satisfied. Although the aim of the research is to investigate the variability around the regression line it was necessary to make sure the regression model satisfied the assumptions including a normal distribution of residual values around the regression line and no auto-correlation within the residuals. As discussed in Chapter 2, section 2.8, residual values are defined as the difference between the observed and predicted values of the dependent variable, so

$$Y_{res} = Y - Y_i \tag{4.2}$$

Interpretation of absolute residuals defined by equation 4.2 may be difficult however because of the relative difference between the magnitude of the residual and the observed value (Johnston, 1980). For example, if in case 1, $Y = 96$ and $Y_i = 93$ then the residual value is 3; in case 2, $Y = 8$ and $Y_i = 5$ then the residual value is also 3. Although both residuals have the same magnitude it is clear that the difference is much less important in the first case – a difference of 3 against a predicted of 96 compared with a difference of 3 against a predicted of 5. Relative residuals defined as

$$Y_{Rres} = (Y - Yi)/Yi \tag{4.3}$$

where the absolute residual is expressed as a ratio of the expected value, emphasise the relative importance of differences between residual values in relation to the predicted value. However, when equation 4.3 is represented graphically, the series of lines plotted according to the magnitude of the residual value, diverge from the regression line at the point at which the line crosses the Y-axis resulting in a difference in the slope of the line (Johnston, 1980). For any regression, the larger the value of X, the smaller the relative residual value. To avoid the problems of scale involved when comparing one or more absolute or relative residuals, standardised residuals were used in this research. Standardised residuals express the values of $Y-Y_i$ in terms of the normal distribution of residuals. The standard deviation associated with the variance of the normal distribution is known as the *standard error of Y* and describes the portion of variance in the dependent variable (Y) not explained by the independent variable (X). The standard deviation of this residual variance can be defined as

$$SE_Y = S_Y\left(\sqrt{1-r_{XY}^2}\right) \quad (4.4)$$

where S_Y is the standard deviation for Y and $1- r_{XY}^2$ is the unexplained portion of the variance in Y. Standardised residuals are defined as

$$Y_{Sres} = (Y - Y_i)/SE_Y \quad (4.5)$$

Standardised residuals can be located on the regression scatter diagram in relation to standard error lines (+1 S.E.and –1 S.E.) around the regression line. As with standard deviation of a normal distribution these enclose approximately 68 % of all observations. Compared with relative residuals, standardised residuals have two advantages. First, they can be associated with a clearly defined statistical distribution (the normal). Second, they comprise bands that run parallel to the regression line and therefore do not give undue emphasis to the residuals in Y related to either large or small values of X.

The parallel standard error bars related to the regression line were used as a basis for identifying the distance of residuals from the regression line. The dataset was divided into five classes based on the standard error line at +1 and –1 running parallel to the regression line (shown in figure 4.3 where residuals are colour coded according to class). The data between these lines were sub-divided further at +0.5 and –0.5 to allow a more detailed investigation of residuals of varying magnitude and direction in relation to the regression line resulting in five classes defined in table 4.6.

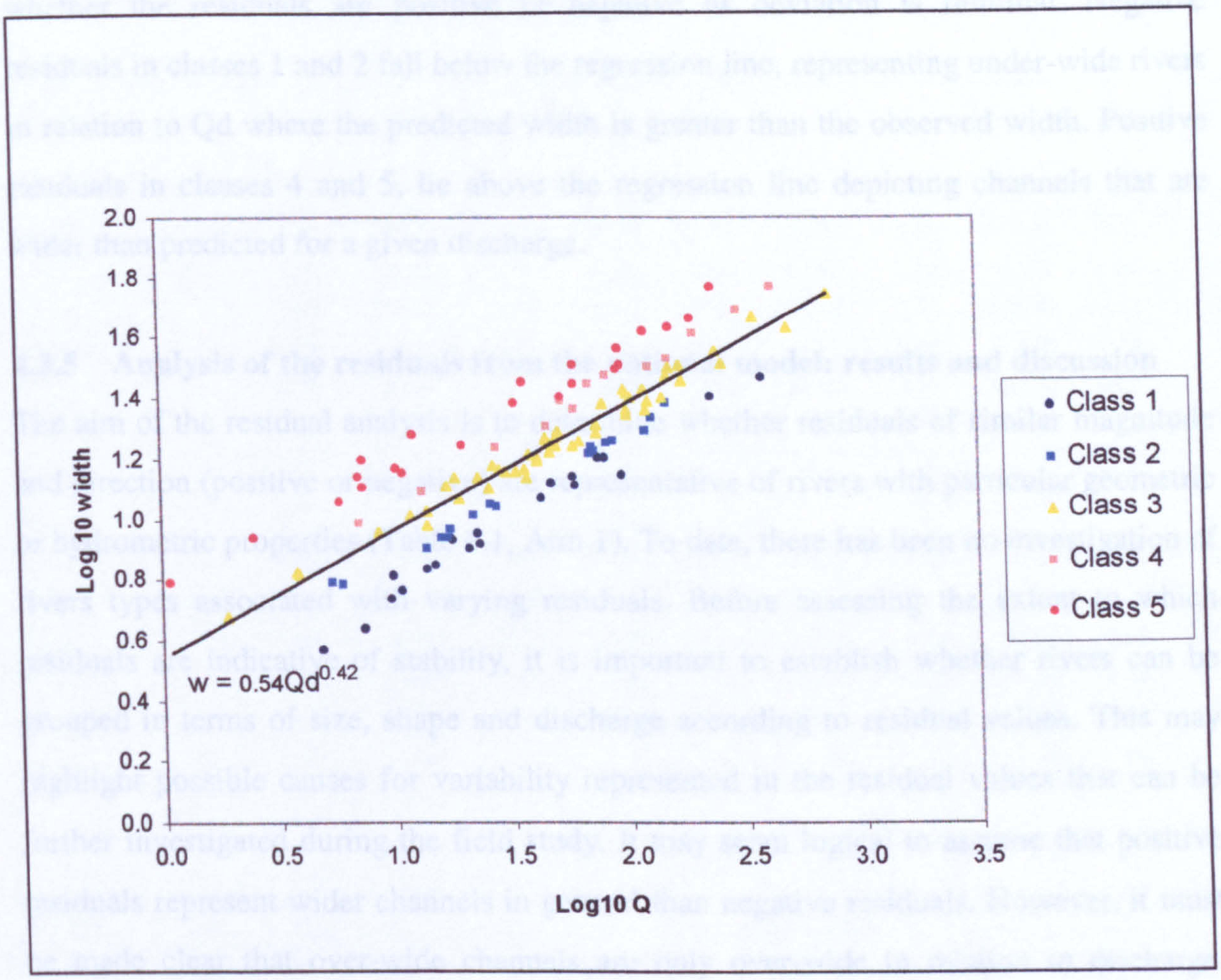


Figure 4.3 **The relationship between bankfull width (w) and dominant discharge (Qd) for 124 sites according to class**

Table 4.6 **Table showing class boundaries based on standard error line and the number of observations within each class.**

Class name	Class boundaries	Number of sites in each class
1	> -1.0	21
2	-1.0 to -0.5	19
3	-0.5 to 0.5	49
4	+0.5 to 1.0	14
5	>1.0	21

Class 3 from 0.5 to -0.5 includes data closest to the regression line irrespective of whether the residuals are positive or negative as deviation is minimal. Negative residuals in classes 1 and 2 fall below the regression line, representing under-wide rivers in relation to Qd where the predicted width is greater than the observed width. Positive residuals in classes 4 and 5, lie above the regression line depicting channels that are wider than predicted for a given discharge.

4.3.5 Analysis of the residuals from the national model: results and discussion

The aim of the residual analysis is to determine whether residuals of similar magnitude and direction (positive or negative) are representative of rivers with particular geometric or hydrometric properties (Table 4.1, Aim 1). To date, there has been no investigation of rivers types associated with varying residuals. Before assessing the extent to which residuals are indicative of stability, it is important to establish whether rivers can be grouped in terms of size, shape and discharge according to residual values. This may highlight possible causes for variability represented in the residual values that can be further investigated during the field study. It may seem logical to assume that positive residuals represent wider channels in general than negative residuals. However, it must be made clear that over-wide channels are only over-wide in relation to discharge. Further investigation is needed to assess the differences between rivers in terms of size, shape and dominant discharge. Descriptive statistics of width, depth, W:D ratio and discharge (shown in table 4.7) are used to analyse the characteristics of rivers in each class and the extent to which the regression model is over or under-estimating river width.

In terms of discharge, classes 1, 2 and 5 have a similar mean Qd of between 55 and 60 m^3s^{-1}, compared with classes 3 and 4 which have higher mean discharge values of 95 and 120 m^3s^{-1} respectively. This indicates that on average, more extreme residual magnitudes tend to be associated with rivers with lower Qd values whereas rivers located closer to the regression line have a higher Qd values on average. However, the standard deviation and ranges about the mean values portray a more detailed picture.

Table 4.7 **Descriptive statistics of geometric and discharge data and residual values for each class, for both log and untransformed values**

Class	1		2		3		4		5	
Qd	**Log10**	**Normal**								
Mean	1.48	59.69	1.55	54.91	1.71	95.74	1.85	120.36	1.43	59.69
Standard Deviation	0.49	89.77	0.46	46.40	0.52	128.92	0.51	123.54	0.64	66.39
Range	1.90	378.99	1.44	143.31	2.59	734.18	1.78	416.90	2.34	235.92
Minimum	0.69	4.87	0.74	5.45	0.28	1.90	0.85	7.10	0.03	1.08
Maximum	2.58	383.86	2.17	148.76	2.87	736.08	2.63	424.00	2.37	237.00
Count	21	21	17	17	51	51	13	13	22	22
W										
Mean	0.98	11.06	1.09	13.50	1.26	20.35	1.41	28.86	1.34	25.32
Standard Deviation	0.23	6.51	0.19	5.65	0.21	10.08	0.22	13.90	0.25	13.56
Range	0.90	25.45	0.60	17.85	1.06	50.05	0.78	48.20	0.98	51.70
Minimum	0.56	3.65	0.78	6.05	0.68	4.75	0.98	9.60	0.79	6.10
Maximum	1.46	29.10	1.38	23.90	1.74	54.80	1.76	57.80	1.76	57.80
Count	21	21	17	17	51	51	13	13	22	22

Depth

	1	2	3	4	5
Mean	1.12	0.98	1.25	1.51	1.11
SD	0.41	0.33	0.53	0.67	0.56
Range	1.65	1.21	2.25	2.07	2.31
Minimum	0.40	0.54	0.36	0.62	0.38
Maximum	2.05	1.75	2.61	2.69	2.69
Count	21	17	51	13	22

W:D ratio

	1	2	3	4	5
Mean	7.96	10.43	13.00	12.74	15.07
SD	3.56	3.75	7.24	3.54	4.59
Range	12.42	15.72	30.14	13.78	23.51
Minimum	3.51	4.36	5.22	8.00	6.93
Maximum	15.93	20.08	35.35	21.78	30.44
Count	21	17	51	13	22

Standardised residuals

	1	2	3	4	5
Mean	-1.43	-0.79	-0.01	0.73	1.55
SD	0.34	0.13	0.26	0.19	0.35
Range	1.13	0.49	0.99	0.47	1.22
Minimum	-2.16	-0.99	-0.50	0.50	1.03
Maximum	-1.03	-0.50	0.50	0.98	2.24
Count	021	17	51	13	22

Difference in width

	1	2	3	4	5
Mean	-5.25	-3.46	-0.05	5.79	8.97
SD	2.54	1.38	1.78	3.59	5.09
Range	10.35	5.32	9.72	12.07	20.78
Minimum	-13.07	-6.28	-3.67	1.67	2.50
Maximum	-2.72	-0.97	6.05	13.74	23.29
Count	21	17	51	13	21

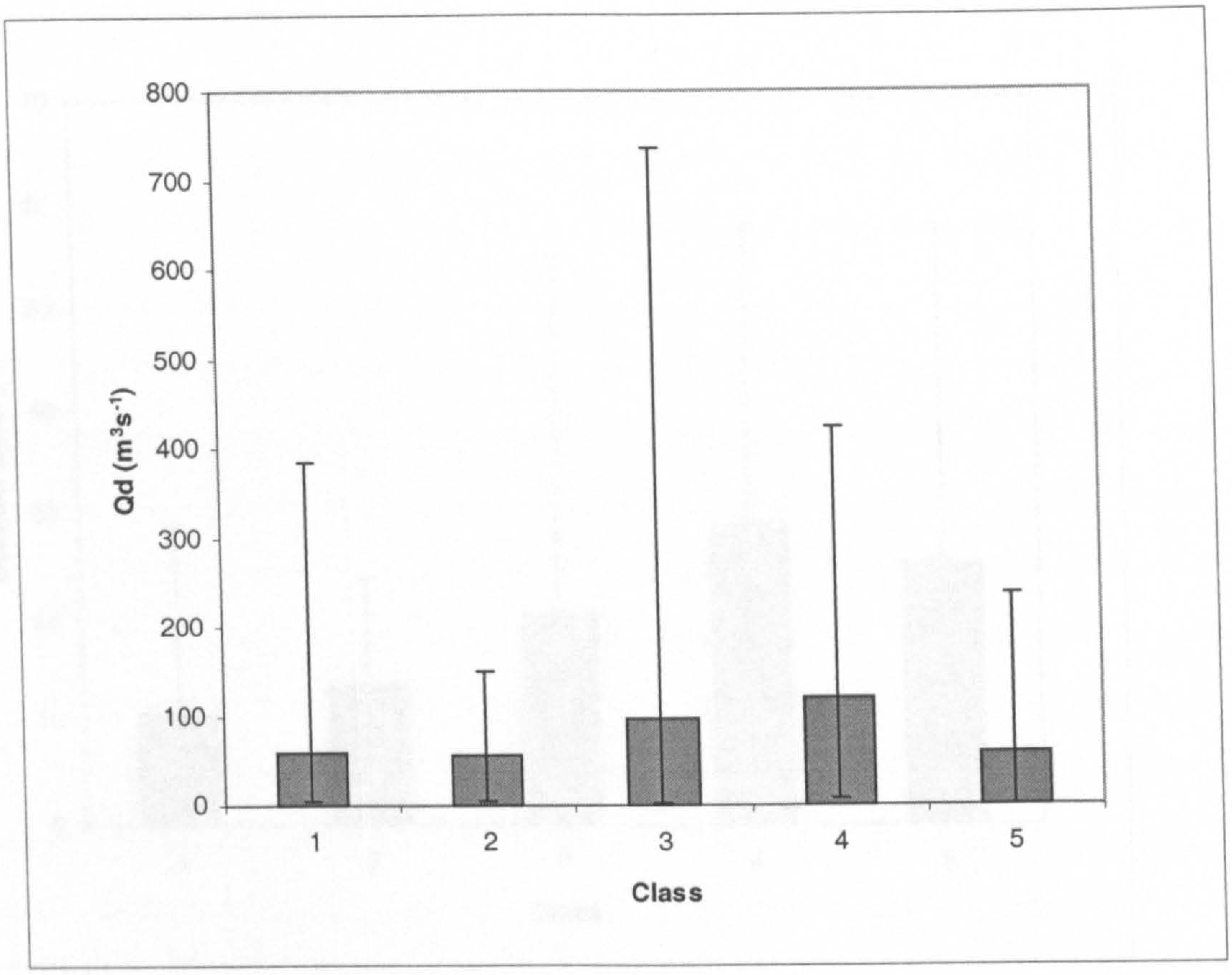


Figure 4.4 **Graph showing the mean and range of Qd for each class**

Although class 3 has a higher mean Qd compared with classes 1, 2 and 5, it also contains a wider range about the mean, including the River Ems (46) with one of the lowest Qd values in the dataset (1.90 m^3s^{-1}), and the River Esk (114) with one of the highest Qd (736.08 m^3s^{-1}). Class 4 contains the second largest range of rivers in terms of Qd and both classes 3 and 4 have a similar standard deviation of approximately 120. Class 1 rivers also have a larger range than classes 2 and 5, indicating that although the mean values are the same in all three classes, rivers in class 1 with the highest negative residual values are not limited to a particular Qd. In contrast negative residuals in class 2 and extreme positive residuals in class 5 show least variation about the mean with standard deviations of 46.40 and 66.39 respectively. This suggests that residual values in these classes may be influenced by Qd.

Channel width partly reflects the trends of Qd with large ranges of channel width in classes 3 and 4 (approximately 50m) and a relatively small range of rivers in terms of width in Class 2 (17.85m). This suggests that rivers closest to the regression line and over-wide rivers in class 4 occur in a wide range of river types compared with under-wide rivers that occur in a relatively narrow band of rivers.

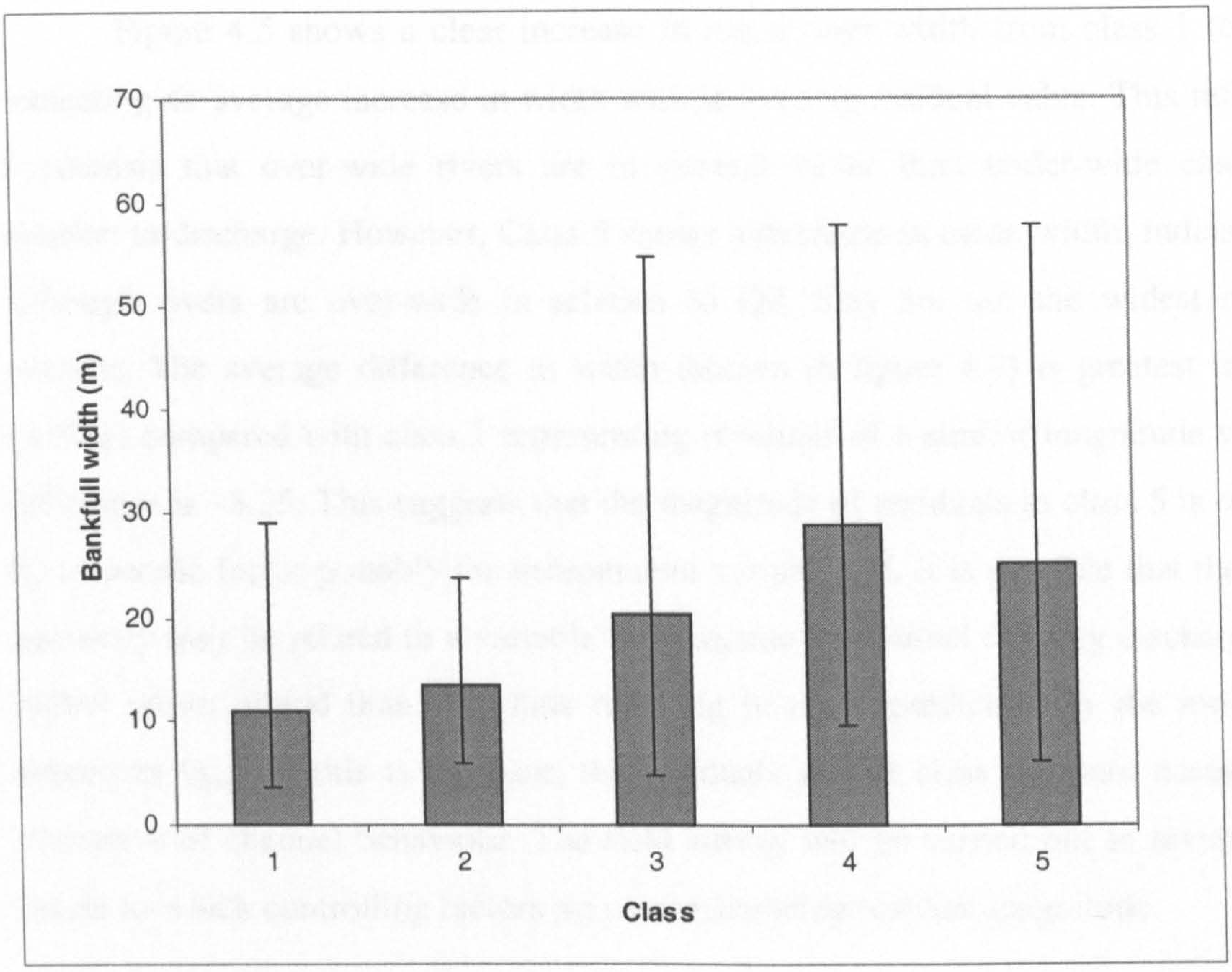


Figure 4.5 Graph showing mean and range of width values for each class

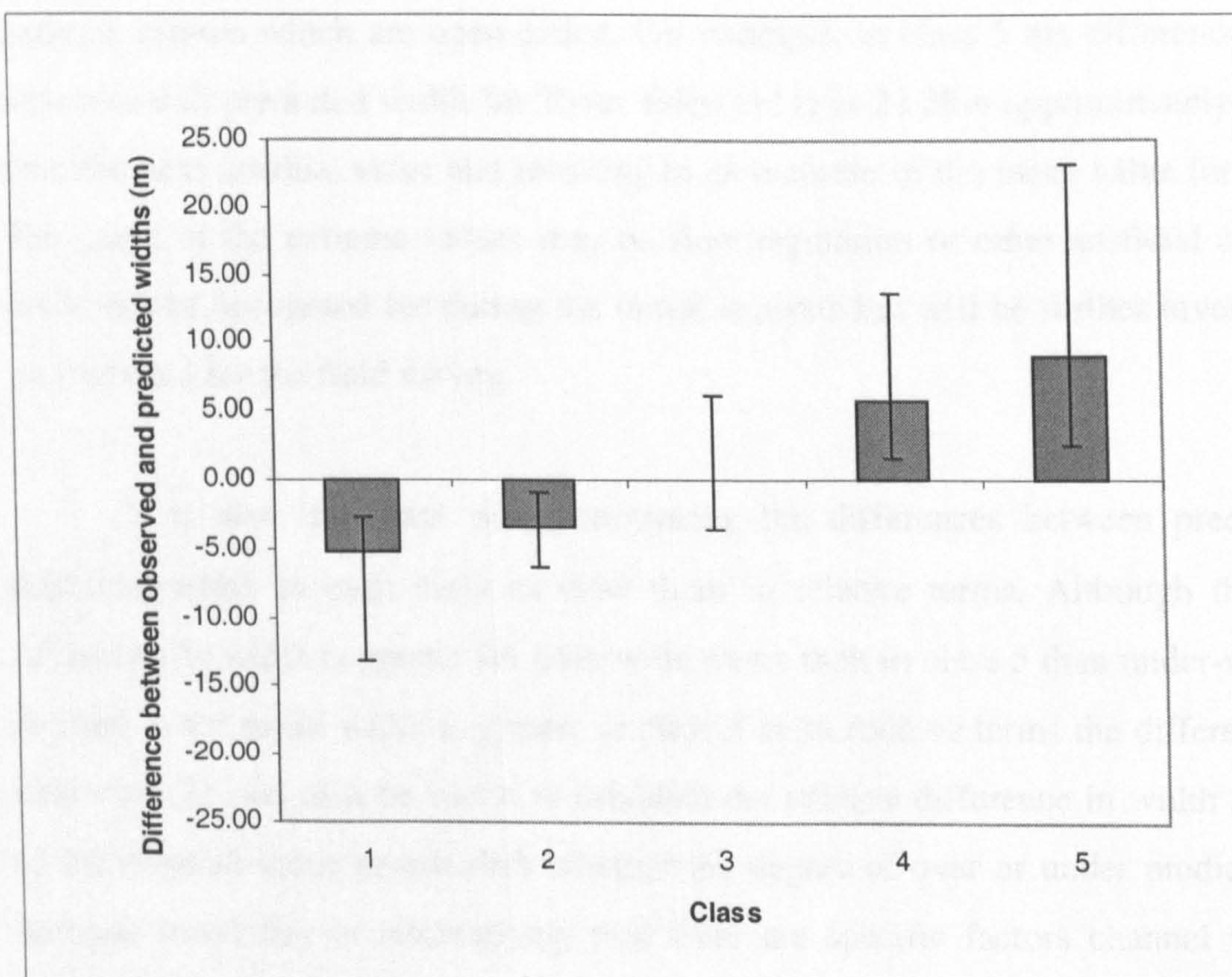


Figure 4.6 Graph showing the mean and ranges of the difference between observed and predicted widths

Figure 4.5 shows a clear increase in mean river width from class 1 to class 4 indicating an average increase in width with increasing residual value. This reflects the hypothesis that over-wide rivers are in general wider than under-wide channels in relation to discharge. However, Class 5 shows a decrease in mean width, indicating that although rivers are over-wide in relation to Qd, they are not the widest rivers on average. The average difference in width (shown in figure 4.7) is greatest in class 5 (8.97m) compared with class 1 representing residuals of a similar magnitude where the difference is –5.25. This suggests that the magnitude of residuals in class 5 is controlled by a specific factor possibly the independent variable Qd. It is possible that the channel geometry may be related to a variable flow regime or channel forming discharge with a higher return period than Q_{maf} thus resulting in under-prediction by the model when related to Q_{maf}. If this is the case, the residuals in this class may not necessarily be indicative of channel behaviour. The field survey will be carried out to investigate the extent to which controlling factors may be influencing residual magnitude.

The use of the mean values for each class must be treated with caution however, as a single observation can greatly influence the overall average, particularly in the extreme classes which are open ended. For example, in class 5 the difference between observed and predicted width for River Eden (111) is 23.29m approximately 8m more than the next residual value and resulting in an increase of the mean value for the class. The cause of the extreme values may be flow regulation or other artificial causes that could not be accounted for during the initial analysis but will be further investigated in site selected for the field survey.

It is also important when comparing the differences between predicted and observed width in each class to view them in relative terms. Although the average difference in width is greater for over-wide rivers than in class 5 than under-wide rivers in class 1, the mean width is greater in class 5 so in relative terms the difference is less important. It may also be useful to establish the relative difference in width in addition to the residual value to establish whether the degree of over or under prediction could indicate instability or alternatively that there are specific factors channel width. The difference in actual width relative to observed width may also indicate the degree to which the natural channel is likely to be able to naturally recover if used in conjunction with geomorphological data obtained from field survey.

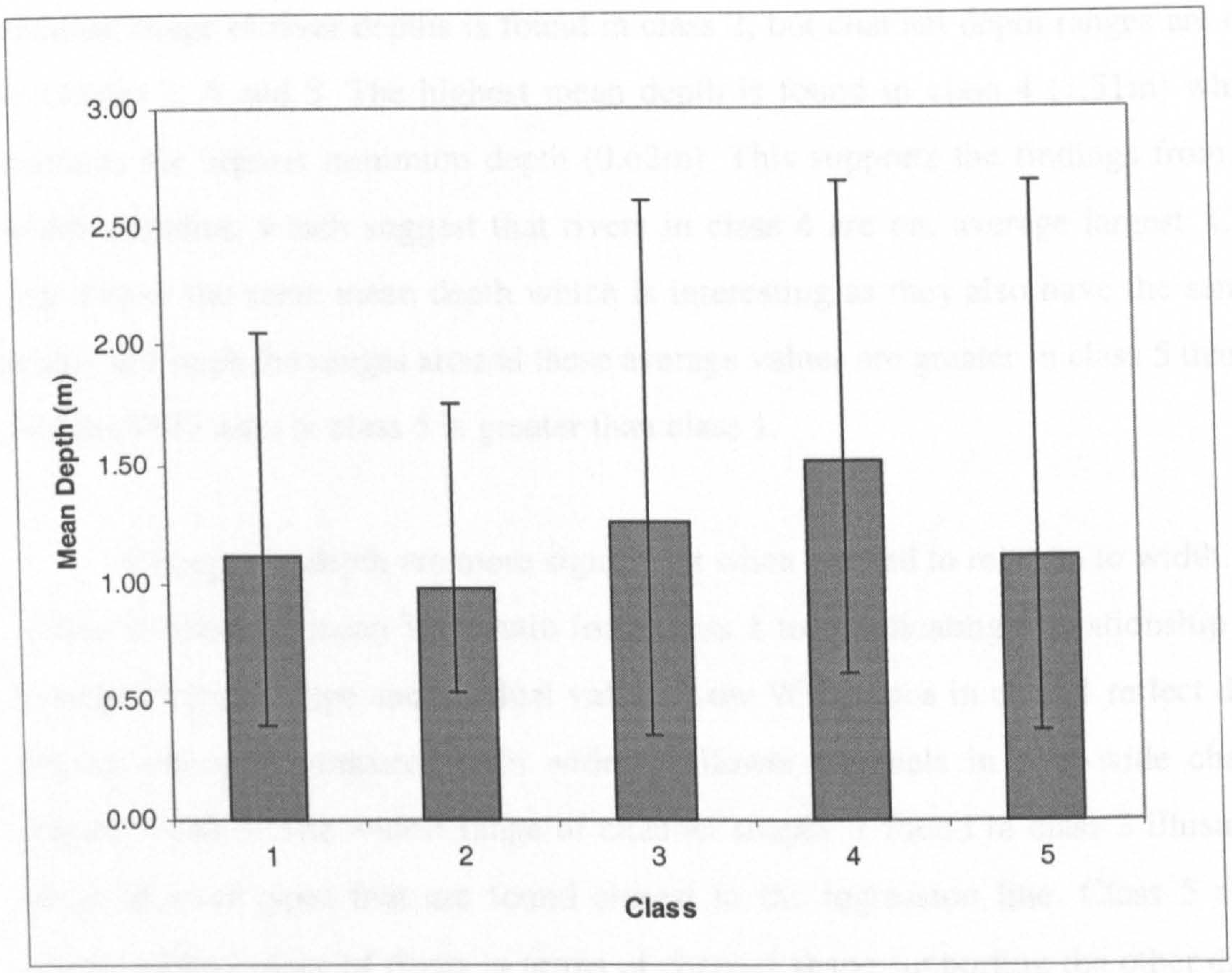


Figure 4.7 **Graph showing the mean and range of mean depths for each class**

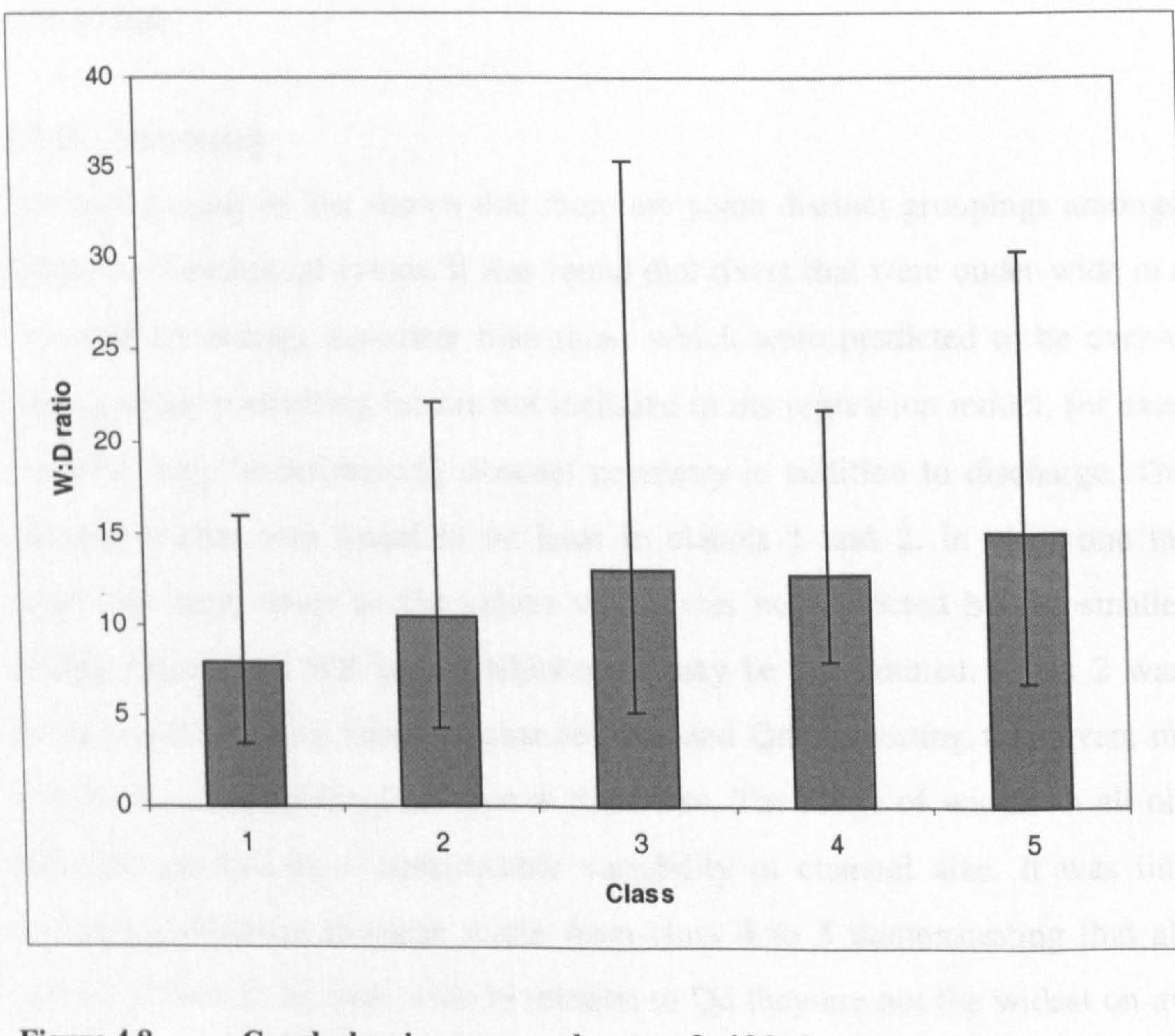


Figure 4.8 **Graph showing mean and range of width:depth ratios for each class**

Mean depth values show no discernible pattern related to residual size. Again the smallest range of river depths is found in class 2, but channel depth ranges are over 2m in classes 3, 4 and 5. The highest mean depth is found in class 4 (1.51m) which also contains the highest minimum depth (0.62m). This supports the findings from Qd and width statistics, which suggest that rivers in class 4 are on, average largest. Classes 1 and 5 have the same mean depth which is interesting as they also have the same mean width, although the ranges around these average values are greater in class 5 than class 1 and the W:D ratio in class 5 is greater than class 1.

Changes in depth are more significant when viewed in relation to width. There is a clear increase in mean W:D ratio from class 1 to 5 indicating a relationship between average channel shape and residual values. Low W:D ratios in class 1 reflect deeper U-shaped channels compared with wider shallower channels in over-wide channels in classes 4 and 5. The widest range of channel shapes is found in class 3 illustrating the range of river types that are found closest to the regression line. Class 5 shows the second largest range of rivers in terms of channel shape supporting the other data which show that there is a relatively large range of rivers in this class. In comparison Class 4 shows the least variation however, which suggests that rivers tend to be of a similar type in this class.

4.3.6 Summary

The initial analysis has shown that there are some distinct groupings amongst the data related to the residual values. It was found that rivers that were under-wide in relation to Qd were on average narrower than those which were predicted to be over-wide. This suggests that controlling factors not included in the regression model, for example bank material, may be influencing channel geometry in addition to discharge. The range of channel widths was found to be least in classes 1 and 2. In class one there was a relatively large range in Qd values which was not reflected by the smaller range in widths suggesting that lateral adjustment may be constrained. Class 2 was the most limited class both in terms of channel size and Qd suggesting that rivers may be of a particular geomorphological type in this class. The range of widths in all other classes however pointed to a considerable variability in channel size. It was interesting to observe a decrease in mean width from class 4 to 5 demonstrating that although the rivers in class 5 are over-wide in relation to Qd they are not the widest on average. The range of river width was greatest in class 3 where there was little difference between observed and predicted width.

Depth values showed no real trend when viewed in isolation from the other data but combined with river width (W:D ratio) there was a clear relationship between the average channel shape and residual values. Rivers in class one had the lowest W:D ratio whereas river in class 5 had the highest. Channels with negative residuals therefore tended to have a more U shaped cross-section on average than rivers with positive residuals which appear to be shallower and narrower, although the range of W:D ratios in class 5 indicates a wide variability about the mean. These initial findings provide the basis for the field survey which investigates the importance of environmental factors in controlling cross-sectional dimensions and river channel adjustment.

4.4 The development of the field investigation (50 sites)

The purpose of the field investigation was to obtain more detailed information about a subset of rivers to identify whether variability within the residuals observed in section 4.3.5 is representative of river channel stability and sensitivity to change or if it can be linked with specific environmental controlling factors. It was impossible within the constraints of the research to investigate all 124 sites, therefore a subset of fifty rivers was selected according to residual magnitude and direction to represent a range of rivers.

4.4.1 Site selection

The intention was to select ten sites from each class to provide a dataset of fifty rivers for field study. The sites were selected from each class at random using a computer generated random selection process, to avoid any geographical bias or intuitive choice that could influence the research findings. Once the sites had been selected, they were sorted by geographical location to enable a fieldwork plan to be constructed. Before visiting each site a brief desktop study was undertaken, where Environment Agency (E.A.) information, notes from previous site visits (Wharton, 1989) and Institute of Hydrology (I.H.) River Flow Measuring Station Information Sheets, were consulted. If no problems became apparent during this stage, the sites were included in the list of sites for fieldwork. When there was any sign of recent disruption to the site, for example flow abstraction increases or the closure of a gauging station, the site was excluded and another chosen.

At each site an initial ground survey was carried out using sections one and two of the geomorphological assessment (Appendix 3). On the basis of the naturalness checklist the site was either dismissed as unsuitable or a stable reach was selected for study. Where a site was deemed unsuitable, due to channelisation at the reach or interference from upstream, another river in the same class which could easily be included in the fieldwork programme was selected. For example, the Musbury Brook at Helmshore Intake (69034) in class 1 had been channelised and suffered from severe bank erosion upstream as a result. The site was therefore not used and another river in class 1 was selected that could be incorporated into the remaining fieldwork programme. Where there were other reasons for not measuring at a particular site, for example due to problems of access or if the river was in flood, the same procedure of choosing a new site was followed.

The sites that were finally selected for field investigation are shown in Table 4.11. As a result of the selection process, which identified some sites as unsuitable for field investigation, the number of sites in each class varied (see Table 4.8). Where sites were unsuitable for measurement, it was not always possible to find and measure new sites in the same class within the constraints of the fieldwork programme and as a result the number of sites in each class varies. The total number of sites was maintained at 50 by increasing the number of rivers in class 3, possible because of the large number of sites within this class and appropriate considering the range of rivers in this class.

Table 4.8 **The number of field sites within each class**

Class	Number of sites
1	10
2	8
3	16
4	5
5	11

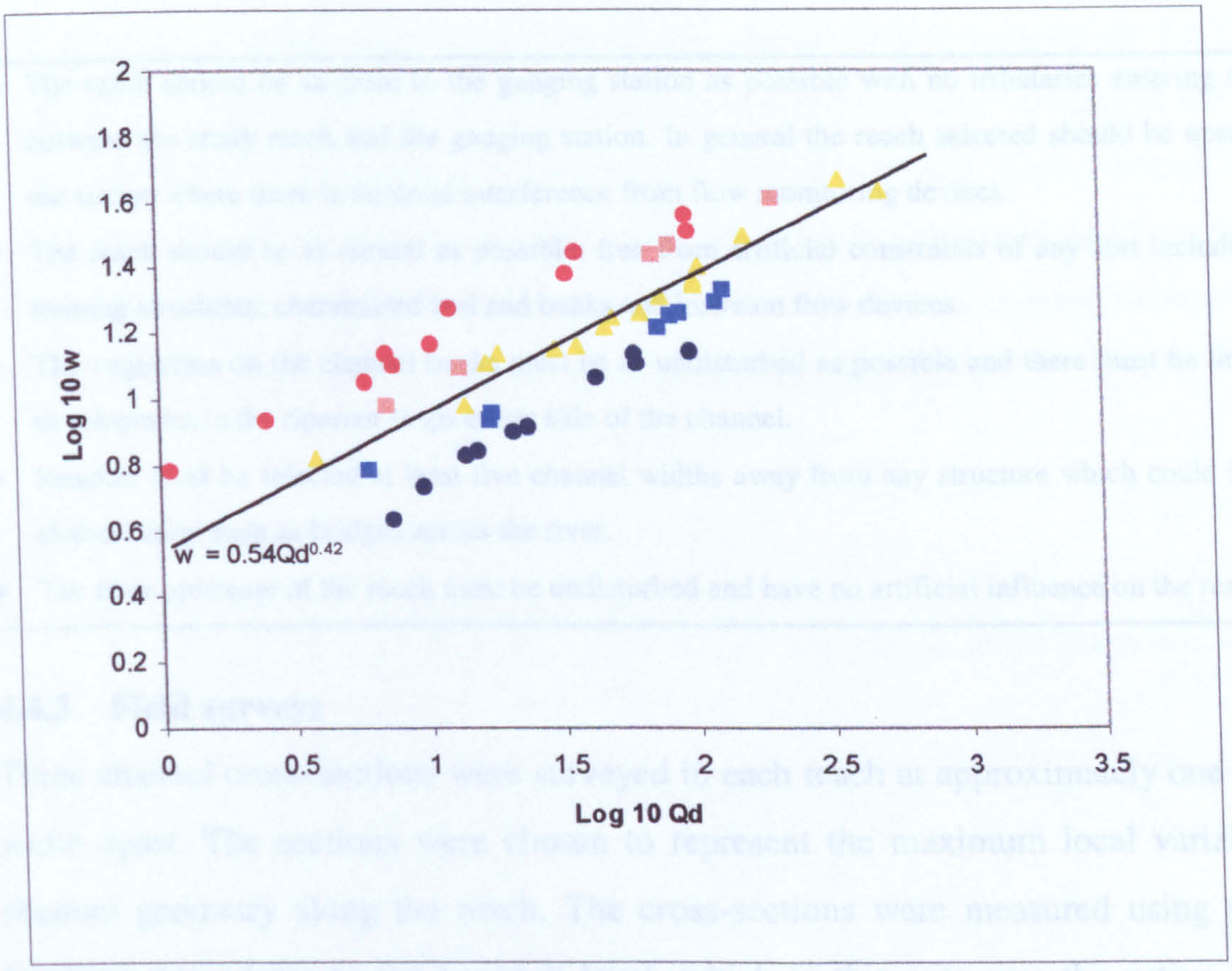


Figure 4.9 **Graph showing the location of the field sites on the residual plot**

4.4.2 Selection of a representative river reach

River reaches of approximately three to five channel widths in length were selected at each site to allow local variability along a geomorphologically unique reach to be included. The reach was selected according to the criteria shown in table 4.9 developed from previous studies of channel geometry. The use of fieldnotes and photographs were also used to try and identify the reach selected by (Wharton, 1989). Often, where the EA owned the land surrounding the gauging station it was possible to see where the reach could easily be measured.

Table 4.9 Criteria used to select field sites

- The reach should be as close to the gauging station as possible with no tributaries entering the river between the study reach and the gauging station. In general the reach selected should be upstream of the station where there is minimal interference from flow monitoring devices.
- The reach should be as natural as possible; free from artificial constraints of any sort including river training structures, channelised bed and banks and instream flow devices.
- The vegetation on the channel banks must be as undisturbed as possible and there must be little or no development in the riparian strips either side of the channel.
- Reaches must be selected at least five channel widths away from any structure which could influence channel form such as bridges across the river.
- The river upstream of the reach must be undisturbed and have no artificial influence on the reach itself.

4.4.3 Field surveys

Three channel cross-sections were surveyed in each reach at approximately one channel width apart. The sections were chosen to represent the maximum local variability in channel geometry along the reach. The cross-sections were measured using standard levelling procedures to the bankfull level, which in this case was the active bankfull level (Hedman et al. 1974; Osterkamp and Hedman, 1982) used by Wharton (1989) and Hey and Thorne (1986) (defined in table 2.2) and shown in figure 4.10. Hedman et al. (1974) were the first to diagrammatically define the active floodplain level as distinct from the valley flat (Williams, 1989) or overtopping level (Wharton, 1989).

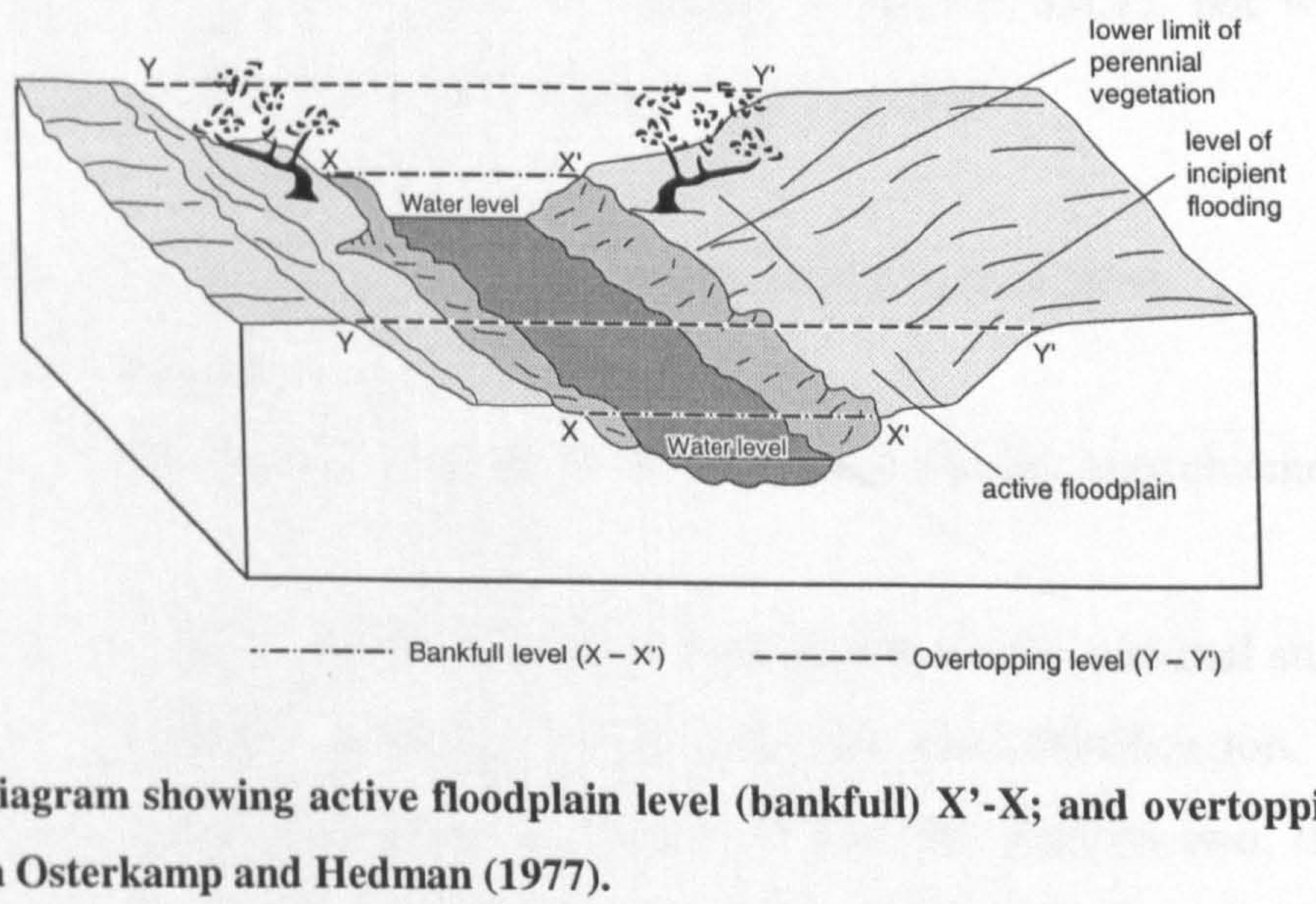


Figure 4.10 Diagram showing active floodplain level (bankfull) X'-X; and overtopping levels Y-Y' modified from Osterkamp and Hedman (1977).

In the field, the bankfull level was recognised using a checklist of hydro-morphological features and marked by the baseline tape across the channel. Where the bankfull level was different on each side of the channel, the lowest bank was taken as the bankfull level shown in figure 4.11 (X - X'). Along each cross-section, survey points were taken according to the geomorphology of the bank so that all breaks in slope, terraces, slumps, bars, the channel edge and water's edge were included. Within the channel according to the width points were sampled every 0.3m, 0.5m or 1m. The cross-sections were plotted using ARCINFO, from which geometric data could be derived.

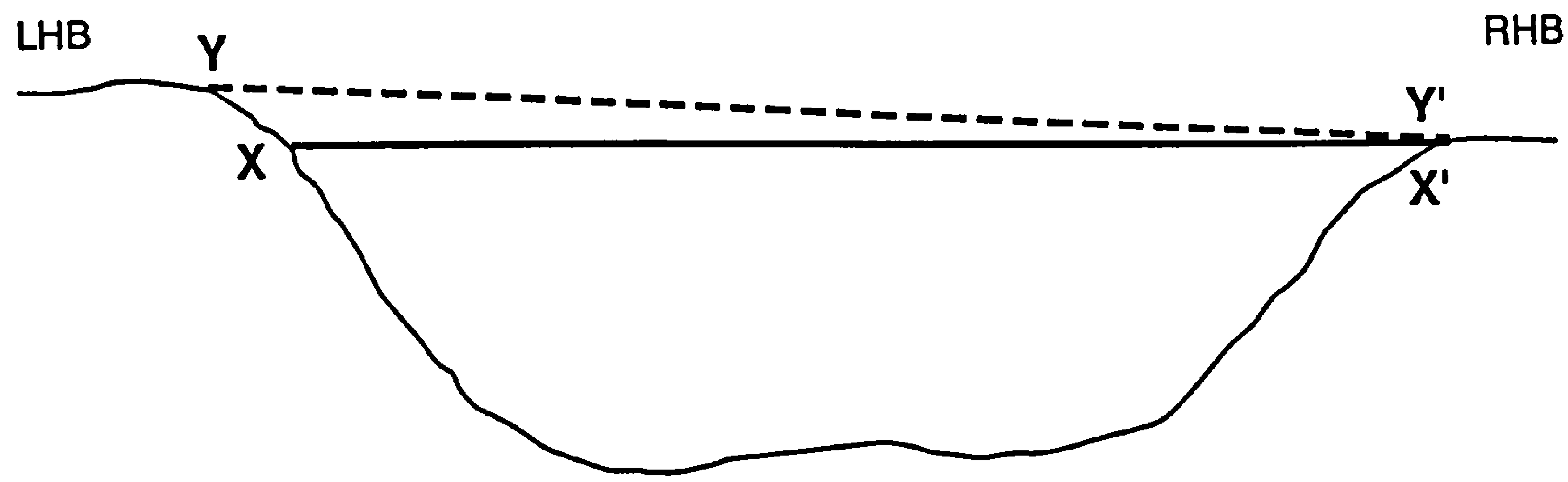


Figure 4.11 **Bankfull level adopted when banks were of different heights**

4.4.4 The development of the geomorphological survey

The geomorphological survey was developed on the basis of previous work on geomorphological surveys described in Chapter 3 (section 3.4.1), but was structured according to the aims of the field investigation which were:

1. To assess the *condition* of the site - the degree of naturalness
2. To assess the *state* of the site - the stability
3. To record information about environmental controls on river channel adjustment

The survey sheets used in the field investigation for the national study are shown in Appendix 3. Section 1 provides details about the site identification, location, past research and an initial description and sketch of the site. Section two, the naturalness checklist, is a detailed assessment of the condition of the channel or the degree to which the channel has been modified. If on arrival, the site was found to be fully channelised indicated by any of the processes shown in section 1, then the river was obviously unsuitable for the study and was dismissed immediately. Parts 2 - 7 show a decreasing level of intervention from 'both bed and banks significantly altered' in section 2 to 'no human influence' in section 7. After completing the naturalness checklist a decision was reached on the suitability of the river section for study. In general, only those sites falling into categories 6 and 7 were accepted, but sometimes naturally adjusted reaches where ancient channelisation occurred for a small length of the channel (no more than 2 metres) could also be accepted where no influence on channel width could be identified.

Section 3, the stability checklist, aimed to assess the extent to which the channel was stable using detailed information about the state of the channel. The checklist of indicators developed by Sear *et al.*(1995) was used as a method of assessing channel stability. The final section, section 5, based on the River Morphology Survey (Brookes, 1994), in the New Rivers and Wildlife handbook provided general information about the physical nature of the catchment.

4.5 Results from the field investigation

The field investigation was carried out to obtain more detailed information about the factors controlling channel geometry and the stability of the river channel at each site. The results from the geomorphological surveys are compared with the residual values of each river to identify whether residuals are indicative of stability, in other words, river channel adjustment, or the factors controlling river channel form. Research has previously considered environmental controlling factors in terms of regional variation and the analysis will first consider to what extent the geographical location affects the distribution of rivers of differing residual values.

4.5.1 Geographical distribution

Wharton (1989) found that the residual values from a channel geometry - discharge model developed for flood estimation, were to some extent distributed geographically with high positive residuals occurring in South East and Central England and low residuals, both positive and negative, occurring in the North and West of England. On the basis of this work, Reeves (1994) developed a channel geometry - discharge model for the prediction of channel dimensions and also found that the highest negative residual values occurred in the South West of the country and that there was a tendency towards clustering, suggesting that influential factors may be linked to local environmental conditions.

The distribution of the field sites across the UK is shown in figure 4.12. The limitations of the original database of 124 sites are reproduced in the sub-set of 50 rivers selected for the field survey. There is a lack of rivers in Central and East of England, resulting from widespread channelisation of rivers in this area and problems of locating semi-natural reaches close to gauging stations. Apart from the clear lack of sites in this area, there are no clear national patterns of residual values and most classes do not appear to be geographically restricted, for example class 1 rivers are found across the UK from north east Scotland to south west England.

However, there are several distinct clusters of residuals, for example, a band of rivers in class 5 stretches west from the Thames Estuary and a small cluster of class 1 rivers occurs in the South West. This suggests that a regional control such as geology may be having an important effect on channel geometry-discharge relationships. A high proportion of Class 5 rivers are located on chalk acquifers and are groundwater fed, for example, the Rivers Avon, Dun and Wylye. The flow regimes are baseflow dominated and show slow response times to high magnitude events, suggesting that the use of Q_{maf} as channel forming discharge may not be appropriate in these rivers. The cluster of rivers in the South West, may also be related to the underlying geology. The Fowey (66), Lynher (63) and Camel (67) all flow off Bodmin Moor, underlain by Bodmin granite, an impermeable rock which combined with peat moorland vegetation, results in responsive flow regime which could influence channel geometry - discharge relations in this area. The majority of class 2 rivers are found in North-East England and Scotland with a cluster of rivers in Northumbria that may also be related to a geological control.

The effect of altitude was also considered as much of the research on fluvial geomorphology in the UK has considered differences between upland and lowland rivers. Altitude, which can broadly be taken to represent climate, rainfall and river channel development was found to have no relationship ($r = 0.07$) with residual values and no patterns could be identified. However, the absolute altitude of rivers may not be representative of the location of the river reach relative to the catchment and the ratio of station altitude to maximum catchment altitude was calculated for each river as a measure of relative altitude and compared with residual values, illustrated in figure 4.13.

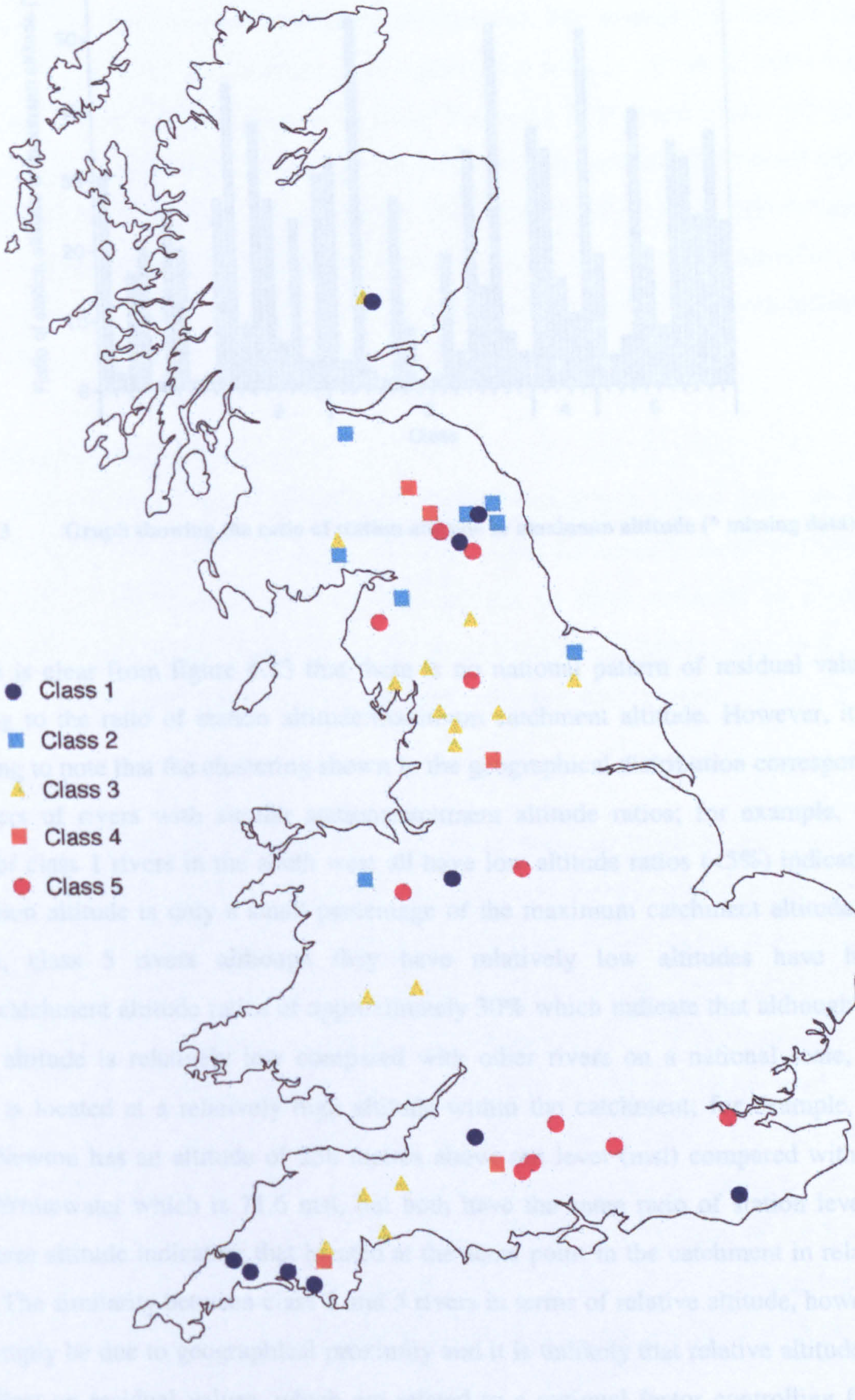


Figure 4.12 The location of field sites across the UK

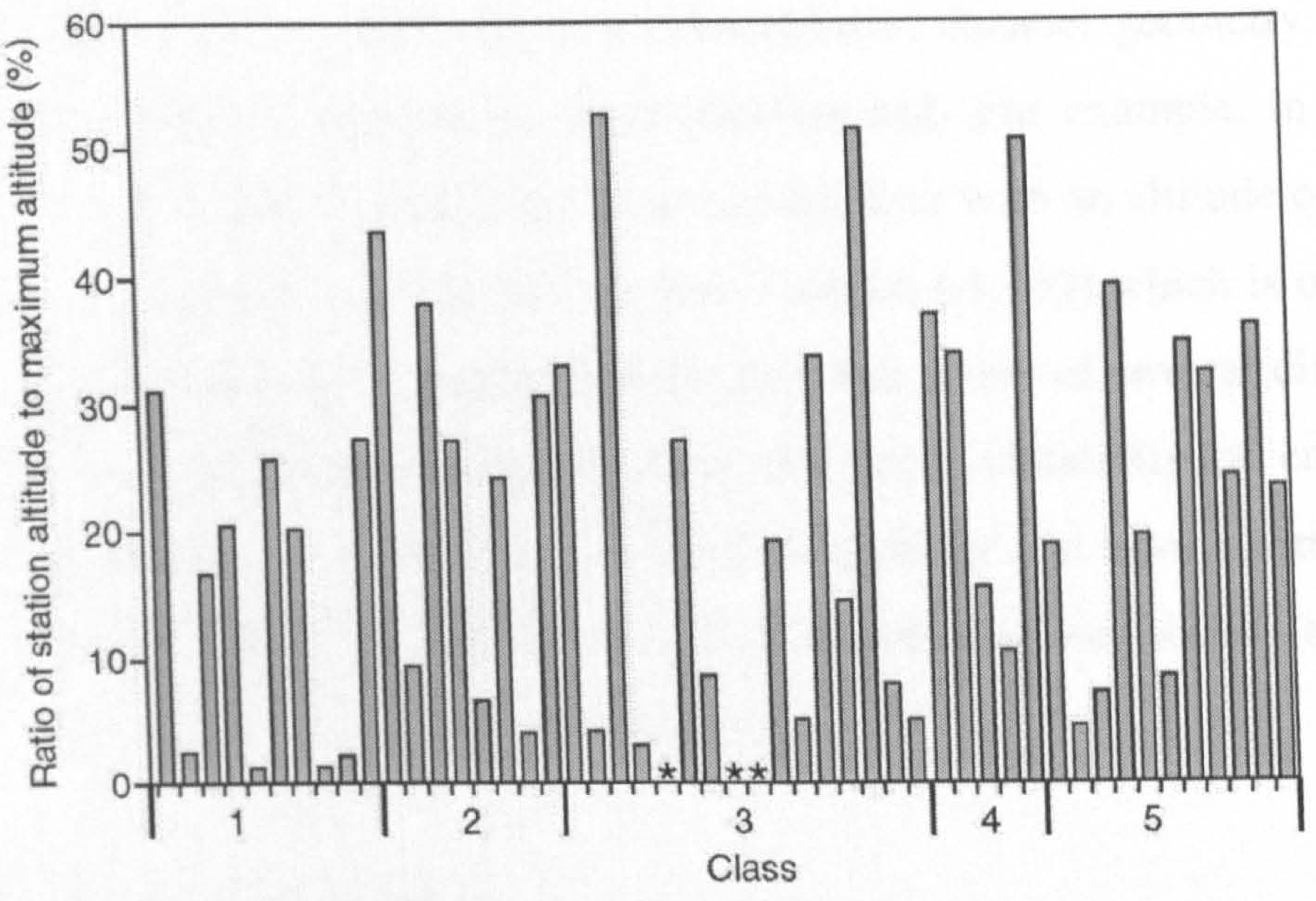


Figure 4.13 **Graph showing the ratio of station altitude to maximum altitude (* missing data)**

It is clear from figure 4.13 that there is no national pattern of residual values according to the ratio of station altitude:maximum catchment altitude. However, it is interesting to note that the clustering shown in the geographical distribution corresponds to clusters of rivers with similar station:catchment altitude ratios; for example, the cluster of class 1 rivers in the south west all have low altitude ratios (<5%) indicating that station altitude is only a small percentage of the maximum catchment altitude. In contrast, class 5 rivers although they have relatively low altitudes have high station:catchment altitude ratios of approximately 30% which indicate that although the station altitude is relatively low compared with other rivers on a national scale, the station is located at a relatively high altitude within the catchment; for example, the River Newton has an altitude of 256 metres above sea level (msl) compared with the River Whitewater which is 71.6 msl, but both have the same ratio of station level to maximum altitude indicating that located at the same point in the catchment in relative terms. The similarity between class 1 and 5 rivers in terms of relative altitude, however, may simply be due to geographical proximity and it is unlikely that relative altitude has any effect on residual values, which are related to a regional factor controlling factor such as geology.

It is clear that there is no relationship between altitude or relative altitude and residual magnitude or direction and as a consequence, channel geometry - discharge relationships cannot be characterised as upland-lowland. For example, in class 1 the River Alwin, which could be described as an upland river with an altitude of 156.4 msl, has a similar residual value (-1.550) to the River Yealm (-1.553) which is only 5.5 msl. The use of relative altitude does highlight the fact that rivers of several different types occur at locations throughout the catchment and local variability of environmental controls is important. Macro-scale factors such as geology can have a direct effect, as appears to be the case in class 1 and 5, but local factors that vary locally both between and within river systems must also be considered.

4.5.2 Local controlling factors

The main controls that combine to influence channel geometry at a local scale, are bed material type, bank materials and vegetation which were discussed in detail in Chapter 2. This section will examine the influence of each of these variables on channel morphology using the information from the geomorphological survey, section 4, and assess to what extent the residuals represent local environmental controls.

i) Bed materials

Bed material type and size is important in terms of bed-load transport and associated changes in bed-levels and velocity. For the national study, bed material type was defined according to the modal size of bed material size observed at each of the cross-sections. Classification of surface sediments is generally done by eye when assessing the distribution of substrate types in a stream reach (Gordon *et al.*, 1992). Grade scales for particle size are presented in Gordon *et al.* (1992, p.195) and were used as an approximate guide and are as follows; sand/silt <2mm; gravel 2-62mm; cobbles (sometimes referred to as gravel for example, Hey and Thorne, 1986) 64-256mm; boulders, only moved during peak flow events >256mm. On the basis of the findings silt, sand and gravel were grouped together with silt/sand often occurring together. Mixed bed material, refers to a composite bed material types and sizes with bedrock. Several patterns emerged from the results shown in table 4.10.

Cobble bed streams are the most common and classes 3 and 4 are dominated by these types of rivers. They are mobile bed streams and indicative of active sediment transport. Boulder bed streams are all upland channels found in the headwaters of the catchment, but are not specific to one class, again illustrating that residual values cannot be classified according to upland-lowland. The only class that is dominated by a particular bed material type is class 2 for which five out of the nine rivers were influenced by bedrock. The sand/gravel bed rivers were dominated by the extreme residuals (class 1 and 5), rivers which are relatively deep and narrow. Class 3 is dominated by mixed bedload rivers, again indicative of active sediment transport and inputs of sediment from upstream and colluvial sources

Table 4.10 Bedload characteristics of rivers in each class

Class	*Bedrock*	*Boulder*	*Cobble*	*Silt/Sand/Gravel*	*Mixed*
1	Tarset (17)	Newton (2) Alwin (13)	Camel (67) Lynher (63) Yealm (65)	Cuckmere (47) Wellow (70) Weaver (90)	Fowey (66)
2	Leven (26) Usway (11) Coquet (14) Greta (23) Cluden (118)		Almond (5) Caldew (113) Alwen (86)		
3		Croasedale (94) Hebbeck (28)	Tone (68) Harwood (25) Rye (33) Sprint (103) Lugg (73) Otter (55) Exe (54)		Ithon (74) Nith (116) Isla (1) Hindburn (98) Hodder (96) East Dart (59) Crayke (102)
4		Yarrow water (8) Hebden Water (27) West Dart (61)	Leny (4)	Wylye (50)	
5	Rede (16)	Kielder Burn (18)	Darent (45) Derwent (107) Ceiriog (85)	Dove (37) Avon (38) Dun (42) Whitewater (40) Wylye (49)	Snaizeholme (30)

ii) Bank materials

Bank materials were harder to define in the field and were consequently split into four broad classes: clay-silt; silt-sand; sand-gravel; and mixed, composite materials using texture test and visual observation. Figure 4.14 illustrates the distribution of bank materials for each class.

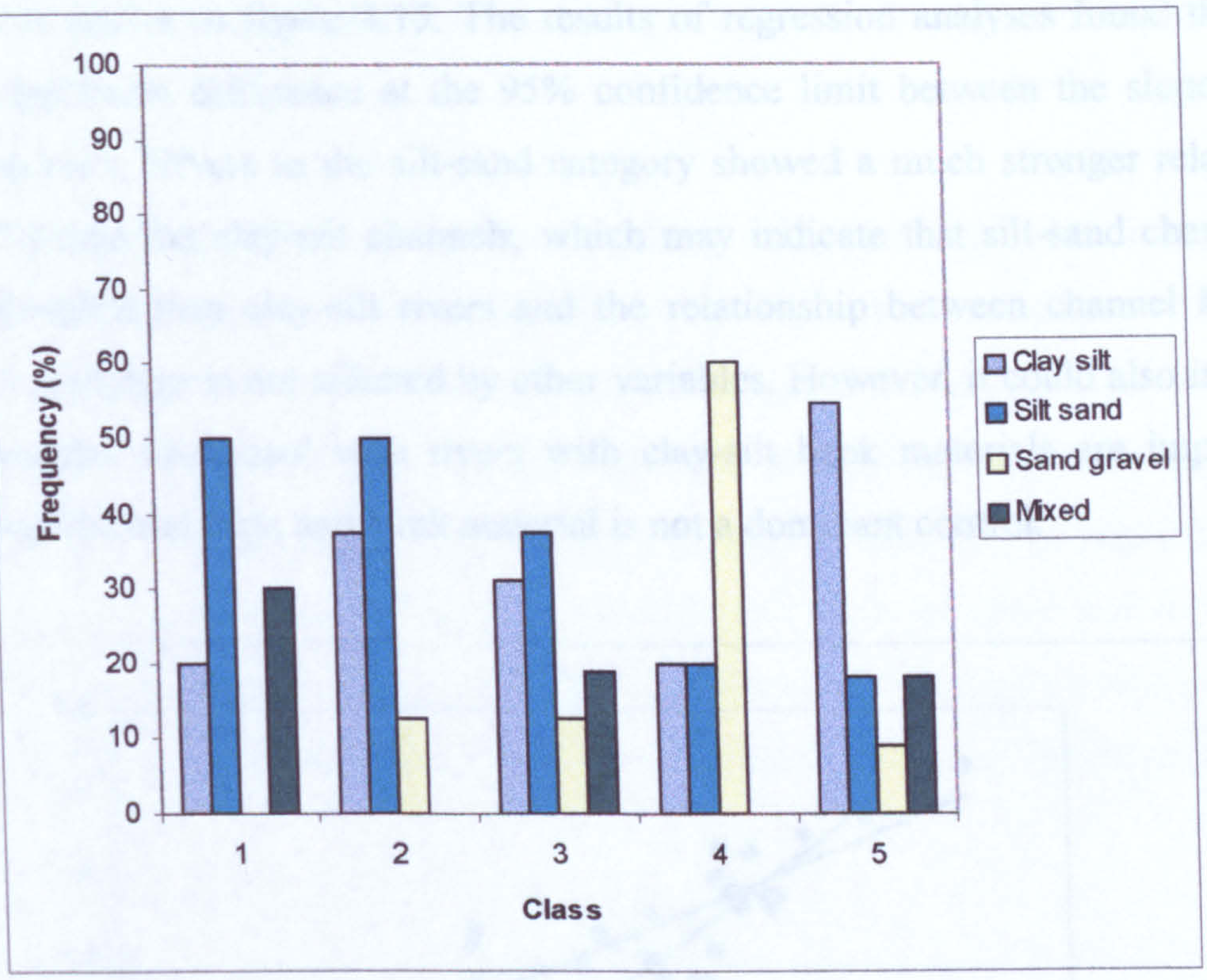


Figure 4.14 **Bank material type corresponding to each class**

Clay-silt banks occur in rivers in all classes but are most common in the extreme classes with approximately 50 % of rivers in classes 1 and 5 composed of clay-silt banks. This suggests that bank materials may have a control on the adjustability of river width with relatively cohesive materials preventing channel adjustment through erosion and the transport of fine silts as opposed to deposition. Class 2 also appears to be influenced by bank materials with 87.5 % of channels with banks composed of clay-silt or silt-sand again relatively cohesive materials. Class 2 was found to the smallest range of widths during the initial analysis and this could be as a result of the combination of bed and bank materials.

Banks composed of mixed material do not occur in either class 2 or 4. Sand-gravel banks are only present in classes 3 and 4, occurring most frequently in class 4, representing over-wide channels that could be a result of non-cohesive bank materials. There is no dominant bank type in class 3, which again illustrates broad ranging channel types in this class. To investigate more fully the extent to which bank materials were dominant on channel-geometry, the relationship between width and depth was plotted separately for rivers with silt-clay and sand-silt banks.

The relationship between width and Qd for rivers with different dominant bank materials is shown in figure 4.15. The results of regression analyses found that there was no significant difference at the 95% confidence limit between the slopes of the regression lines. Rivers in the silt-sand category showed a much stronger relationship (R^2= 0.77) than the clay-silt channels, which may indicate that silt-sand channels are more adjustable than clay-silt rivers and the relationship between channel form and dominant discharge is not affected by other variables. However, it could also imply that other variables associated with rivers with clay-silt bank materials are important in controlling channel form and bank material is not a dominant control.

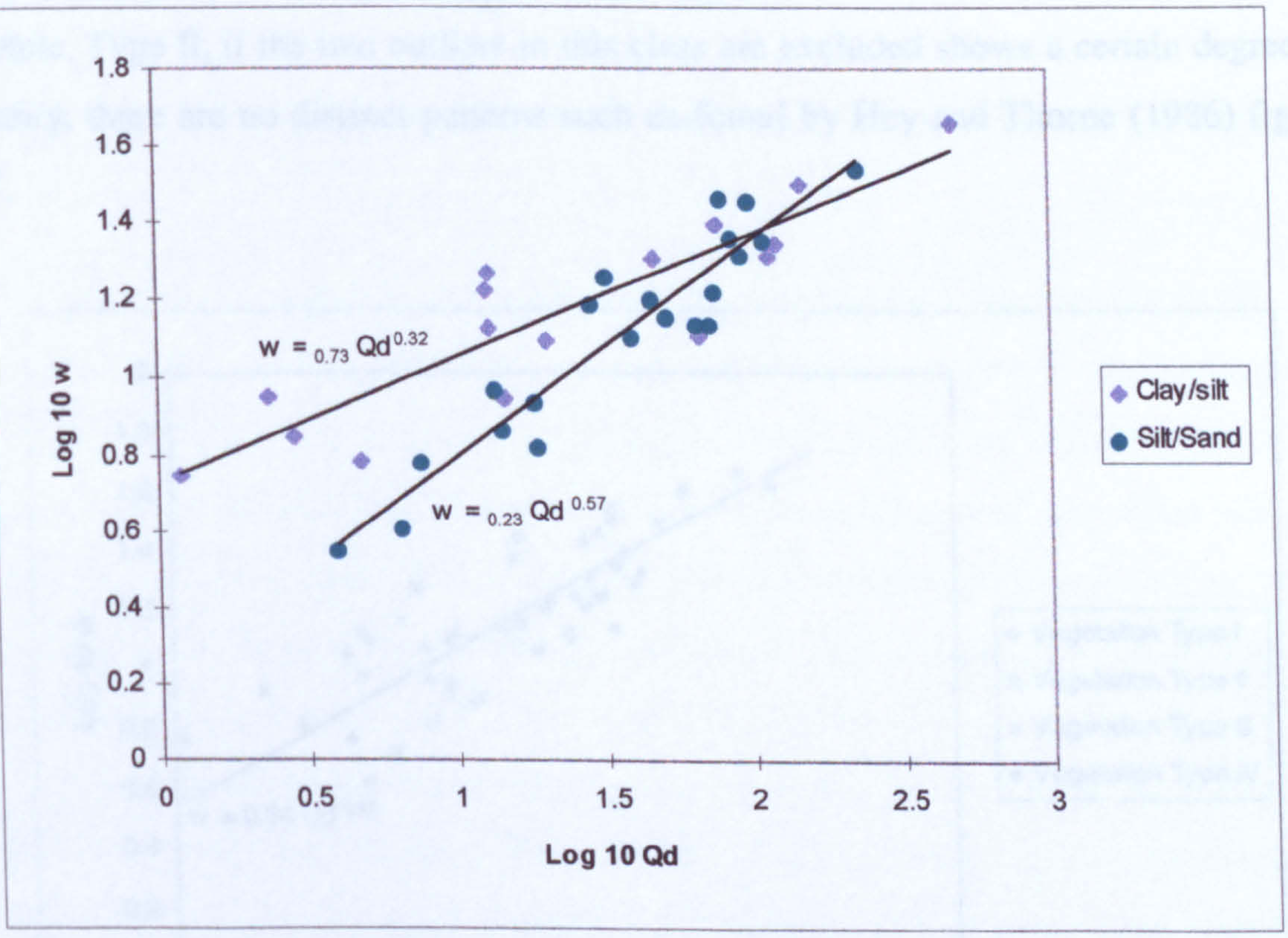


Figure 4.15 The relationship between width and Qd for sites according to bank material

It is interesting that rivers with clay-silt-clay occur mainly in class 1 and 5, the extreme positive and negative residuals. One possibility is that rivers with cohesive banks are less adjustable than non-cohesive banks and therefore changes in channel form occur over long time-scales and the imbalance between Qd and channel geometry may remain for long periods. Thus, although it is clear that rivers with certain bank materials dominate in particular classes, for example class 5, the difference between channel-geometry relationships according to bank material type was not significant. The difference between cohesive and non-cohesive banks may affect the adjustability of channel morphology and could therefore be important in terms of channel stability.

iii) Vegetation

It was expected from Hey and Thorne's (1986) work that vegetation would exert a strong influence on channel width, but this was not found to be the case. Rivers were divided according to Hey and Thorne's (1986) vegetation types and the relationship between width and Qd plotted (figure 4.16). The difference between residual values according to vegetation is not clear. Type I (grassy banks) and II vegetation (0-5% shrub/tree cover) are widely distributed and although there are some visible trends, for example, Type II, if the two outliers in this class are excluded shows a certain degree of linearity, there are no distinct patterns such as found by Hey and Thorne (1986) figure 4.17.

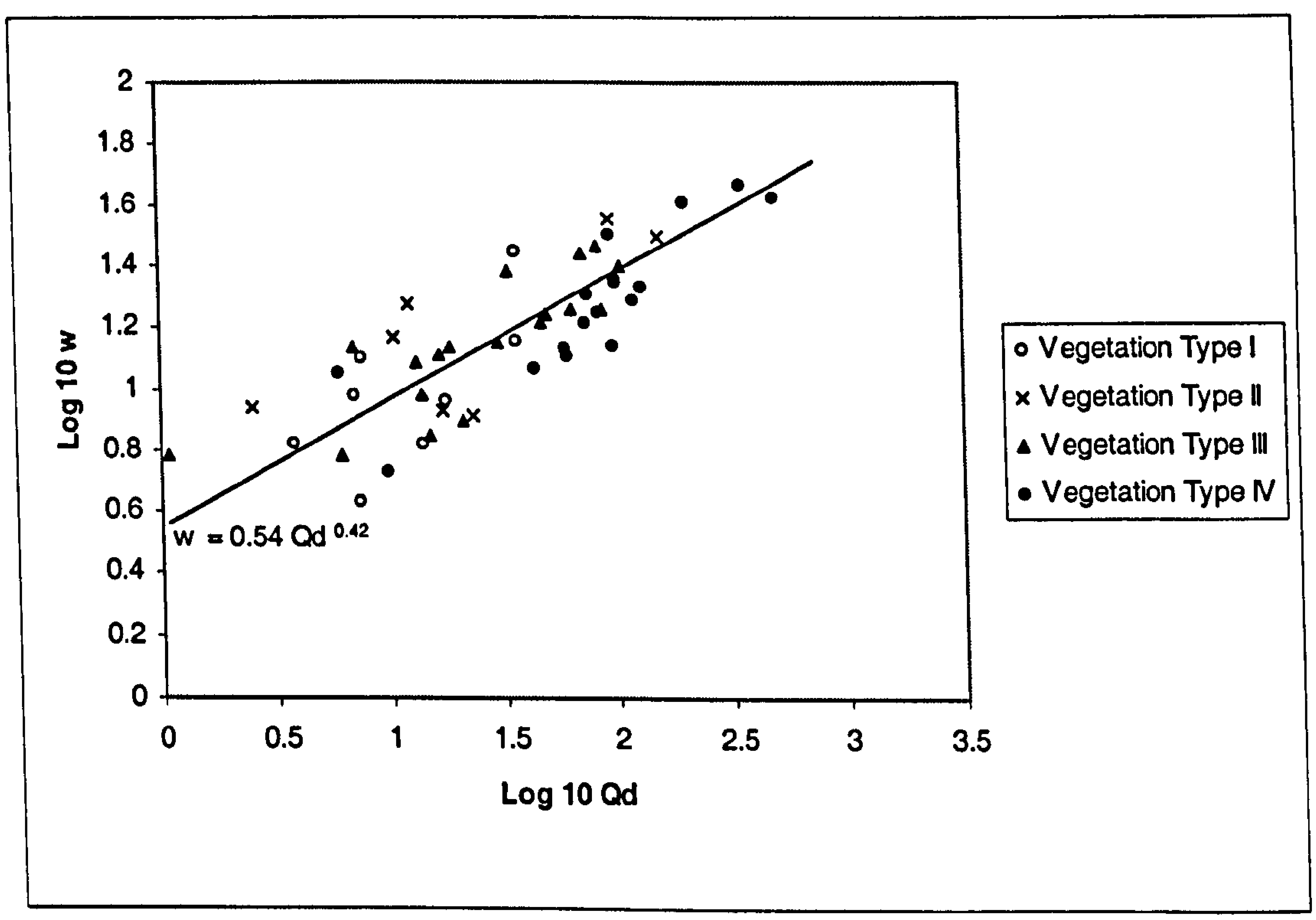


Figure 4.16 The relationship between bankfull width (Log 10w) and Qd (log10 Qd) for the fifty field sites according to vegetation type

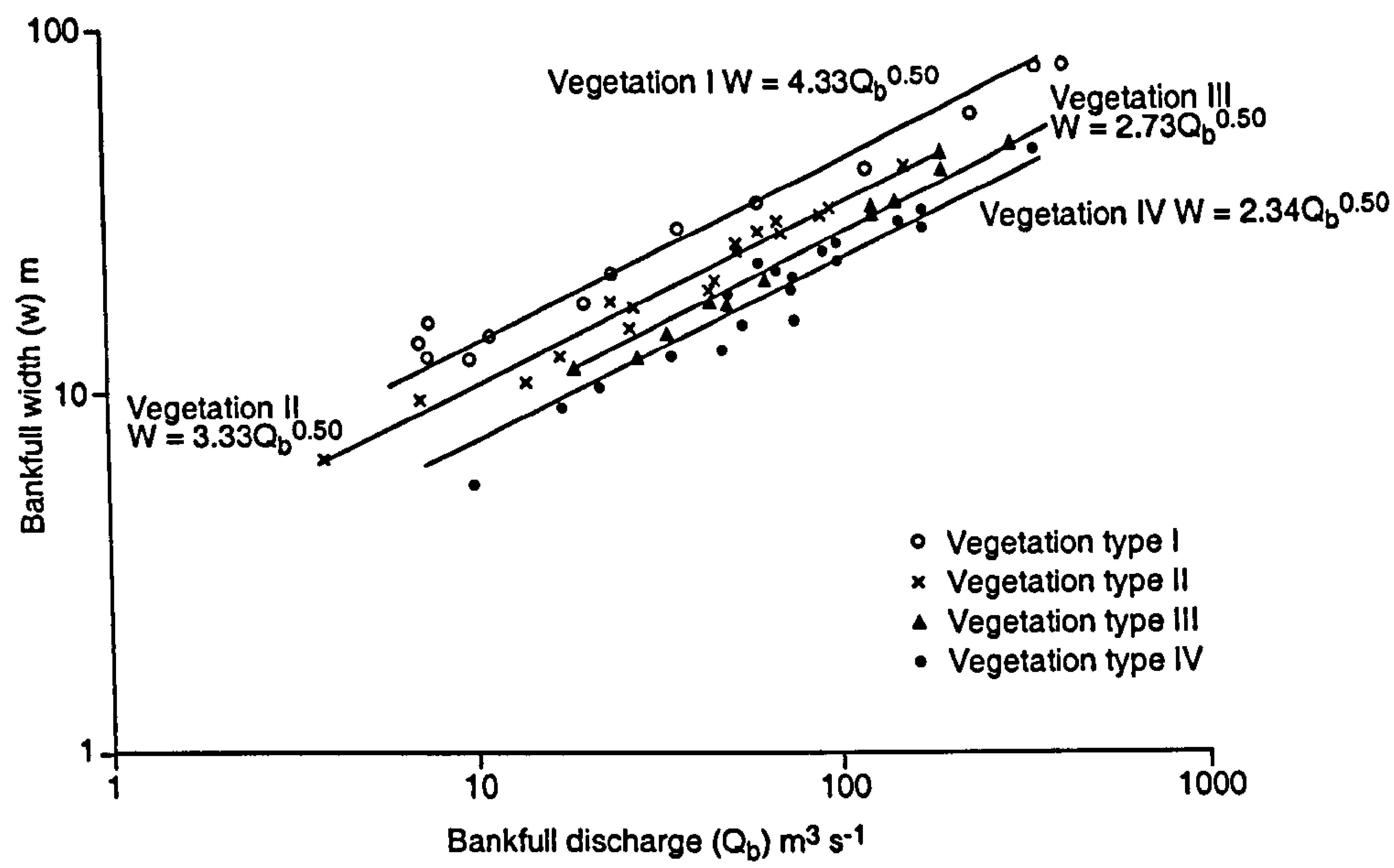


Figure 4.17 Relationship between bankfull discharge and width after Hey and Thorne (1986)

However, it is important to note that the rivers under consideration in Hey and Thorne's study were all gravel-bed rivers and therefore some of the variation of residuals in this research could be attributed to other factors such as bed material type which are masking the effects of vegetation. Whilst vegetation may have some influence on rivers of a similar type, as shown in the gravel bed rivers (Hey and Thorne, 1986), the influence is not significant enough to have a direct impact on the relationship between channel geometry and Qd. It is suggested that the effect of vegetation is indirect and has a combined effect on the stability of the channel. The density of vegetation was considered by Hey and Thorne (1986), but the effect of vegetation may be dependent upon the location of trees banks and whether treelining occurs on one bank, both banks or not at all. The extent of treelining is shown in figure 4.18.

There are no distinct patterns relating the extent of treelining to residual values. When each category of tree lining is observed separately, several apparent trends may be identified. There is an increase of rivers with no treelining from class 2 to class 5 suggesting that over-wide channels are associated with river banks which are free from trees, which could imply that banks without tree lining are more susceptible to erosion. This is confirmed to a certain extent by the high proportion of under-wide rivers in classes 1 and 2 which have treelining on both banks, which could suggest that treelining is preventing width adjustment. However, when all the categories within classes 1 and 5, are viewed together, it is clear that there is little difference in the percentage of rivers with treelining and no treelining, indicating that treelining does not have a dominant effect on channel geometry - discharge relationships, although the indirect effect of vegetation may be important in terms of stability.

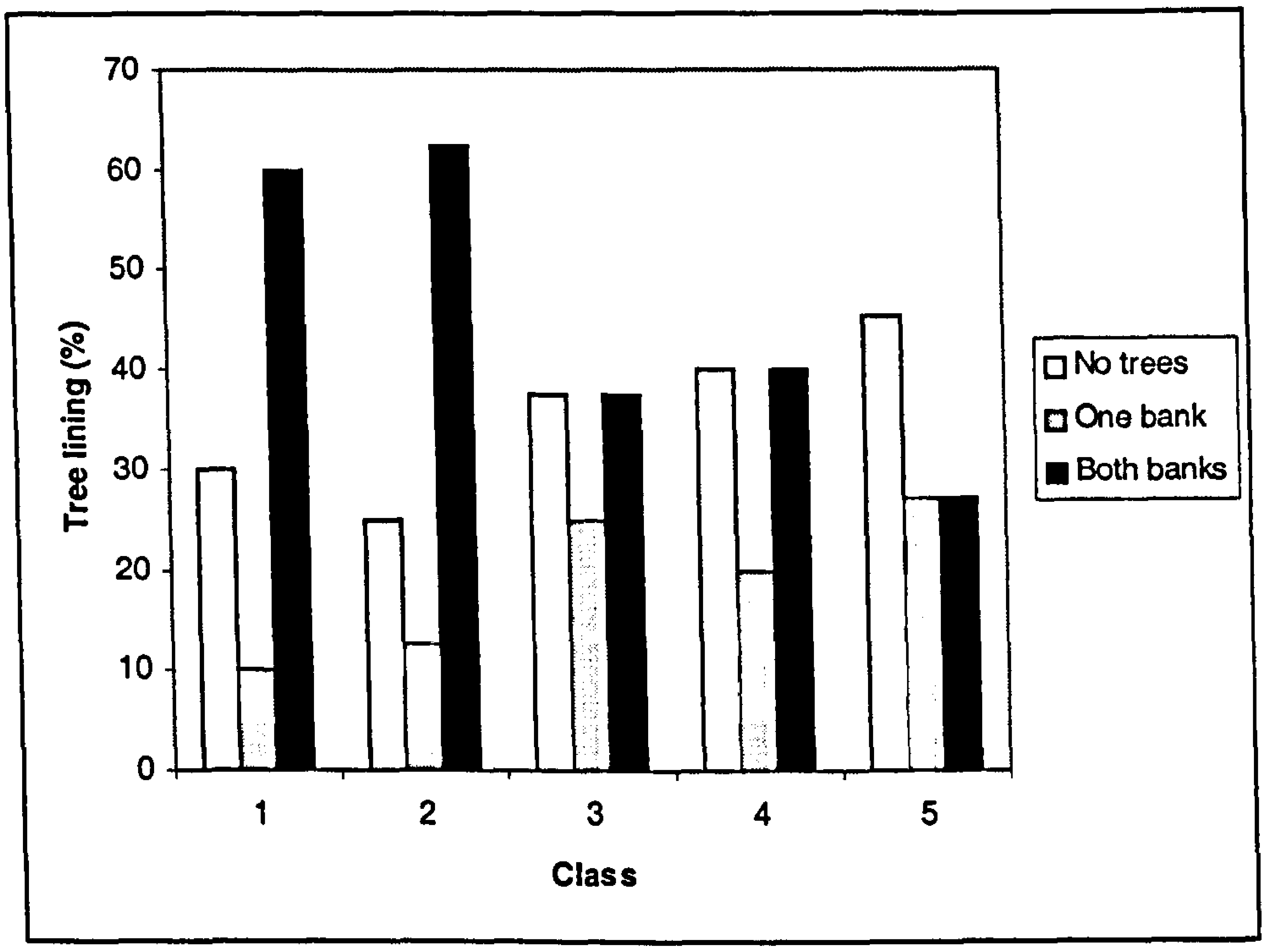


Figure 4.18 Extent of treelining on the river banks

The findings from the analysis of the local controlling factors have shown that different factors are important in controlling rivers in certain classes. Bed material is important in class 2, where the majority of the rivers are bedrock controlled, and in the extreme classes (1 or 5), the dominant bed-material is sand/gravel. In terms of bank materials, there was no identifiable pattern according to class excepting class 5 that was dominated by rivers with clay-silt banks. Class 4, comprising of over-wide channels was dominated by rivers with sand-gravel and it was suggested that the cohesiveness of bank materials may affect the erodibility of the banks and thus the stability. Vegetation did not appear to have a direct control on channel geometry - discharge relations, although again, several trends relating to treelining to erosion could be observed which may be related to river channel stability. The analysis will now focus on river channel stability at each of these sites in the context of these findings.

4.5.3 River channel stability

The use of residuals as indicators of stability described in chapter 3 (section 3.3.4) will be tested in this section using the results from the geomorphological survey, section 3. It is hypothesised that the magnitude of the residual or the difference between the observed value and predicted value is representative of the degree of stability or river channel adjustment occurring within the channel. It is proposed that the type of adjustment is dependent on the direction of the residual value, either positive or negative. Positive residuals, representing over-wide channels, are predicted to be reducing channel width through deposition and negative residuals, under-wide channels, enlarging through erosion. Indicators of erosion and deposition were used to evaluate the dominant type of channel adjustment and the channels were classified accordingly.

Table 4.11 contains site details and information on stability about the characteristics and behaviour of each channel. On the basis of the geomorphological survey, the sites were classified as Eroding (E), Depositing (A) or neither (N) where no process was dominant and the channel was considered as stable. Figure 4.19 shows the percentage of rivers in each category to demonstrate the pattern of behaviour for rivers in different classes.

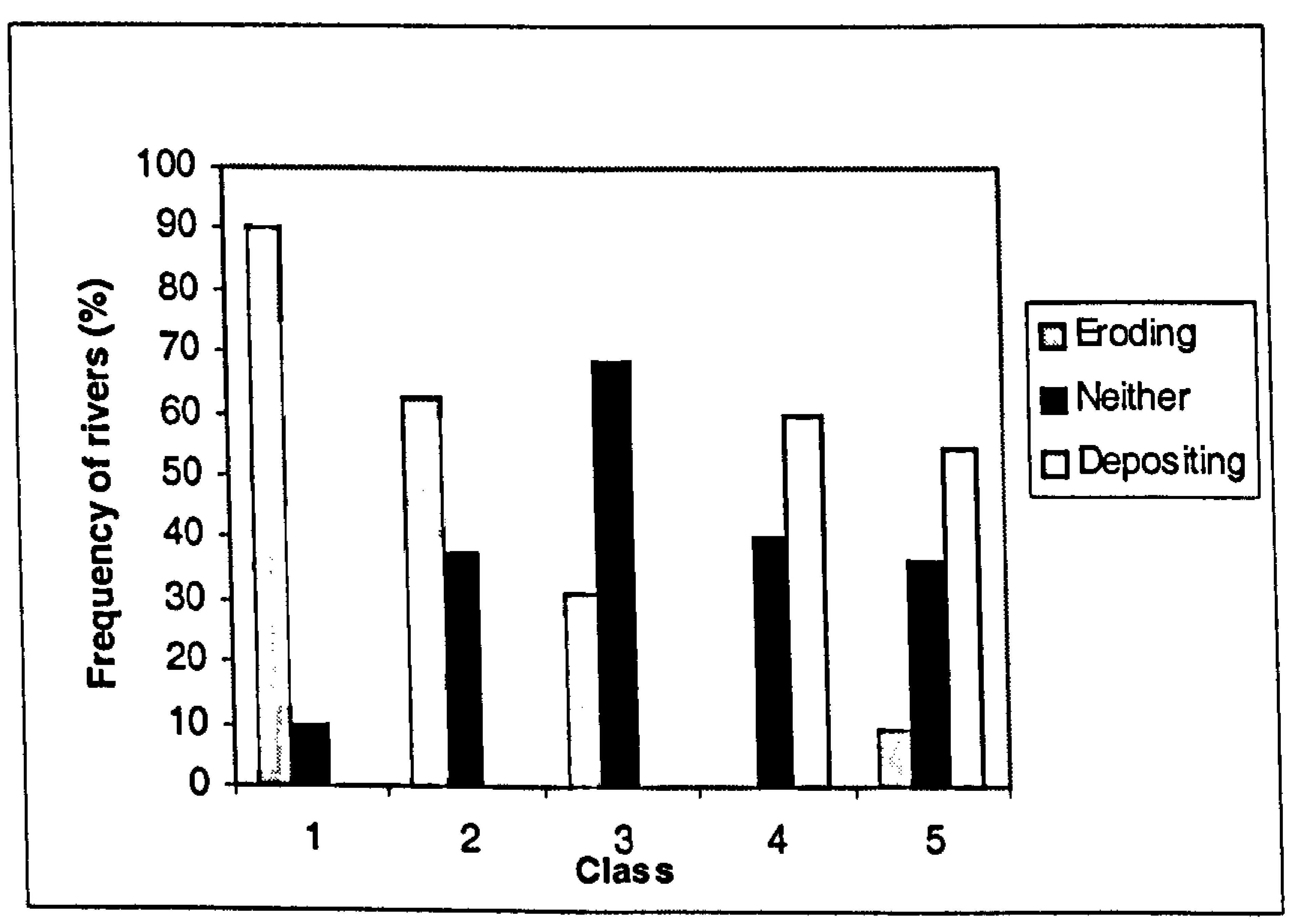


Figure 4.19 **Frequency of rivers in each class which are eroding, depositing or showing no dominant process**

A high percentage (90%) of class 1 rivers was found to be actively eroding and often displayed complex morphologies. Prominent signs of bank failure or unstable

Table 4.11 **Table summarising the stability of each river measured in the field**

Each river is classified according to the dominant process occurring. Symbols: E , eroding; N, No dominant process; D, Depositing.
References: W, Field reports,Wharton (1987, 1988); R, Reeves (1995).

Station	River	ID	E	N	D	Details
Class 1						
15002	Newton	2	#			Underdeveloped channel, terracing, overhanging banks.
48902	Fowey	66	#			Signs of slumping (W), erosion between trees (R), banks eroded.
41016	Cuckmere	47		#		Flashy regime, artificial pumping enhancing flow, clay channel.
68005	Weaver	90	#			Unstable banks (W), undercutting, slumping, complex terracing.
47007	Yealm	65	#			Flashy regime,bank erosion,slumped banks and bent trees (W), active floodplain.
22008	Alwin	13	#			Active floodplain, terraces, bank failure, old channels.
53009	Wellow	70	#			Narrow deep channel, undermined tree roots, severe erosion d/s.
49001	Camel	67	#			Banks severely undermined and overhanging, erosion extensive (R), slumped trees, complex channel, braided downstream.
47004	Lynher	63	#			Severe bank erosion (R), tree roots undermined, banks undercut and eroded behind treeline
23010	Tarset	17	#			Signs of bank erosion, tree roots exposed, banks undercut, failure lines, stable bed.
Class 2						
19002	Almond	5		#		No pool/riffle sequence, no incision or aggradation observed.
22009	Coquet	14		#		Well developed channel, no erosion or deposition, bedrock control.
25006	Greta	23	#			Bedrock and boulder control, LHB severely undercut, trees collapsing into channel (W), erosion evident.
22003	Usway	11	#			Terracing, bedrock control, slumping of topsoil,active channel, step pool sequence.
76009	Caldew	113	#			Undercutting and channel shifting (W), banks undermined, erosion occurring upstream, active channel.
67006	Alwin	86		#		Well developed channel with pool riffle sequence, boulder control on banks, some bank erosion, vegetated side bars.
79005	Cluden	118	#			Trees bent and slumping into river, banks overhanging, terraced bed with bedrock sections, deep V valley, constraining sides.
25019	Leven	26	#			Erosion evident, active floodplain, bank failures, bedrock control.
Class 3						
71003	Croasedale	94	#			Trees slumping into river (W), banks undercutting, bedrock and boulder control, terraced, fallen trees in channel, bank failures.
52008	Tone	68	#			Trees overhanging, fallen trees, varied morphology with mid-channel bar, erosion on RHB, LHS very steep and erosion limited.
25012	Harwood	25		#		Boulder bed stream, high energy and gradient, some erosion but dynamic equilibrium, free to adjust.
79002	Nith	116		#		Mature well developed channel, occasional sign of localised erosion under trees next to river, undercutting.

Class 3	(cont'd)					
55016	Ithon	74		#		Steep sided banks, clay boulder bed, some undercutting of trees but no other signs of erosion.
15001	Isla	1		#		High energy dynamic stable channel in active floodplain, active migration.
27055	Rye	33		#		Some tree undercutting, cobble and boulder bed, stream well developed not migrating.
72003	Hindburn	98		#		Dynamic channel with active erosion and development of bars.
73009	Sprint	103	#			Relatively stable channel, evidence of erosion on LHS, saplings establishing on LH bank, bank failures.
55014	Lugg	73	#			Bankfull clearly defined by trees, no pool-riffle sequence (W), mature vegetation some bank erosion but generally stable.
45005	Otter	55	#			Erosion result of human influence upstream of reach since 1986.
27032	Hebbeck	28		#		Small upland boulder stream, stable, step-pool sequence.
45002	Exe	54		#		Floods regularly onto floodplain, some erosion and slumping RHB.
46005	East Dart	59		#		Upland channel, deep gravel and point bars evident, some aggradation, bank undercutting RHB.
71008	Hodder	96		#		Wide relatively stable channel, bedrock in places, pool riffle sequence developed.
73002	Crayke	102		#		Treelined river, vegatated bars, erosion not dominant, some bank undercutting.
Class 4						
27012	Hebden Water	27		#		Upland, boulder stream, vegetated, no erosion, woodland dominant, variable widths.
43012	Wylye (NB)	50			#	Chalk stream, aggradation LHS build up of sediment and reed bed development..
21011	Yarrow	8			#	Well developed channel, large side bars vegetating baoth sides of channel, pool riffle sequence developed.
18008	Leny	4			#	Fast flowing, shoals and sidebars devloped (W), some erosion with tree slumping, bars and berms developing.
46007	West Dart	61		#		Wide channel with some bank erosion, build up of alluvial gravel on LHS, boulder banks.
Class 5						
23008	Rede	16			#	Wide channel, cobble bars and vegetation of bars in places, erosion not evident.
40012	Darent	45			#	Chalk stream, large scale extraction has reduced flow, vegetation developing at edges on build up of silt.
75003	Derwent	107			#	Compacted weedcovered bed, bars and vegetated island downstream, some erosion.
27047	Snaizeholme	30	#			Small moorland stream on wide, open floodplain, erosion clearly evident in places, stable in others.
43008	Wylye (SN)	49		#		Chalk bed channel, clay banks, weed covered bed, low energy, encroachment of vegetation, slight bank erosion.
67005	Ceiriog	85			#	Wide channel, vegetated bars, shallow sections, recent human, surrounding land management influential
39028	Dun	42			#	Chalk stream, weed covered bed, silt and gravel deposits at side of channel, extensive floodplain
39015	Whitewater	40			#	Chalk stream, build up of silt either side of channel, development of vegetation.
28046	Dove	37		#		Narrow valley, not much vegetation, silt building up in tree roots, erosion evident in places where there are not trees
23011	Kielder	18		#		Upland channel in managed coniferous woodland, boulder bars developed, moss covered, no erosion, width not restricted.
43005	Avon	48		#		Chalk stream, weed covered bed, deep clear, inactive, some bank erosion.

banks indicated by failure lines, were evident in several of the rivers, for example the Weaver (90), which looked similar to a two stage channel in places, but on further investigation was found to be dominated by unstable slumping banks and complex patterns of erosion (see photo 4.1), characteristics previously noted in Wharton's field report of the site from 1988. Slumping was also recorded in the 1997/8 geomorphologcial assessments in the Fowey (66), Camel (67), Yealm (65), Wellow (70) and Alwin (13) shown in table 4.11. Characteristically, the channels in class 1, excepting the rivers Newton (2) and Alwin (13), were deeply incised, with steep, almost vertical banks, which were often undercutting, for example, the River Yealm (65, photo 4.2). This supports the findings from section 4.5.5, in which class 1 was shown to have the lowest W:D ratio of 6.7.

Several different factors appear to be contributing to prevent increases in width and changes in channel capacity may be controlled by changes in depth, demonstrated by scouring in the River Camel (67). Treelining occurred on both banks in 55.6 % of class 1 rivers associated with bank erosion. In the case of the Camel (67), Fowey (66) and Lynher (63), treelining has restricted changes in width and erosion is most severe in places where there are gaps in the vegetation, further indicating the potential for bank erosion. Valley width may also inhibit the lateral expansion of several of the channels, for example in the rivers Camel (67), Fowey (66) and Wellow (63) there is no floodplain buffer and the channel is constrained by the valley walls.

In contrast, the river Newton (2, photo 4.3) and Alwin (13) are small upland rivers, characterised by complex terrace systems, undefined channel boundaries and high energy flow regimes. The Newton has a Qd of 7.43 m^3s^{-1}, but compared with other rivers of a similar discharge, for example, the Wylye (50) and the Dove (37), has a relatively small catchment area (15.4 km^2), suggesting that the hydrologcial regime of the catchment is responsive and prone to high magnitude flow events. This flashy flow regime could promote instability within the channel also found in the River Alwin (13). The geological control on class 1 rivers flowing from Bodmin Moor over impermeable granite (discussed in section 4.5.1), also results in a responsive flow regime which could contribute to instability within the channel system.

Photo 4.1 River Weaver at Audlam (90)

Photo 4.2 River Yealm at Puslinch (65)

Photo 4.3 Newton Burn at Newton (2)

Photo 4.4 River Nith at Friars Carse (116)

For class 2 rivers, erosion remained the dominant process in class 2, with 62.5% of all sites demonstrating signs of erosion, for example, bank undercutting and slumping trees found in the Tarset (17), Leven (26) and Cluden (79005). Although erosion was obvious, it was much less severe than seen in class 1, where erosion was often extreme and the morphology unstable. One of the main factors common to class 2 was that most of the channels had a bedrock or boulder control influencing either bed or bank erosion at one point in the stream which may have constrained channel width. As a result, channels eroded at weaker points within the channels. The highest residuals in this class were found in smaller channels such as the Leven (26) and the Usway Burn (11), both with active floodplains allowing peak flows to overtop frequently, reducing limitations imposed by constraints such as bedrock. The lower residual rivers in class 2 relate to more well-developed channels which are underwide probably as a result of constraints on bank and bed erosion imposed by bedrock controls.

Class 3 represents rivers with the smallest residual values, predicted to be the most stable. The analysis of the residuals (section 4.4.5) showed that the range of rivers in this class is extremely broad in terms of size and Qd and there were no distinct river types that could be associated specifically with low residuals. The main similarity between some of the rivers was an *inactive* behaviour, observable from a lack of erosional or depositional features shown in 69% of rivers. The larger rivers were the most clearly inactive, for example the river Nith (116, photo 4.4), Hodder (96) and Exe (54), which demonstrated stable conditions with few signs of erosion or deposition. However, a similar state could also be observed in small channels such as the Hebden Beck (28) a well established channel showing little evidence of instability within the stream. This condition is referred to as stable by Downs (1995b). Class 3 also contained rivers that were free to adjust, high energy boulder bed streams that showed some evidence of erosion but not extensive and balanced by deposition of boulders.

There appeared to be two dominant types of behaviour in class 3, *inactive stability* and *active stability* where the channel was free to adjust in planform but maintained stable channel dimensions, referred to as lateral migration by Downs (1995b). Inactive stability was demonstrated in rivers such as the Nith (116) and the Hodder (96) where there were few signs of erosion or deposition and little evidence of channel change. Other channels, for example, the Harwood (27, photo 4.5) and Isla (1,

Photo 4.5 Harwood Beck at Harwood (25)

Photo 4.6 River Isla at Forter (1)

photo 4.6) showed signs of *active stability*. Interestingly, at both extremes of this class the rivers displayed similarities to the rivers of adjacent classes.

For example, the Croasedale and Tone both showed more prominent signs of erosion and the Croasedale also showed a bedrock control, characteristic of class 2. Sites with positive residuals in class 3 for example, the East Dart, showed signs of deposition as well as erosion with bars and berms developing similar to some of the channels in class 4 including the West Dart.

Classes 4 and 5, encompassing the positive residuals representing over-wide rivers, contain a range of rivers in terms of behaviour and morphology. There is a high proportion of wide cobble bed channels, characterised by depositional features shown in 66% of the rivers. The Yarrow (8, photo 4.7), Leny (4, photo 4.8), Rede (16), Derwent (107), and Ceiriog (85), all showed signs of active deposition which were not present in classes 1,2 or 3, excepting the Hindburn (3). In some cases, revegetation was occurring on the bars, for example, the Yarrow (8) shown in photo 7, Rede (16) and Ceiriog (85) and it was clear that the channels were depositing, a process which, if continued, could result in a decrease in bankfull width. Class 5, surprisingly also contained rivers that were very different from class 4 in terms of morphology and behaviour. The rivers were much smaller, as discussed in section 4.4.5, and showed very little sign of change with 50% of rivers showing no dominant process operating. The channels were over-wide in relation to dominant discharge, yet often appeared to be flowing close to bankfull, suggesting that the channels are controlled by a steady flow regime, characteristic of groundwater fed streams which dominate class 5, for example the River Dun (42) and River Avon (48). It could also be a result of bed aggradation and weed growth reducing channel capacity forcing the water to bankfull levels, clearly evident in photos 4.9 and 4.10. Several of these channels were showing signs of aggradation (37.5%) including the Darent (45) and Whitewater (40), but the proportion was significantly less than rivers in class 4. In general however, there was little activity in class 5 rivers that could be the result of controlling factors specific to the rivers in this class. This was supported by the findings from the initial residual analysis of rivers that suggested that the similar behaviour of rivers may be a response to a common controlling factor or channel geometry could be related to a different reference discharge. The River Wylye (43012), class 4, was similar to class 5 rivers but aggradation was occurring to a much greater extent, accounting for the smaller residual value. The Snaizeholme Beck was similar to

Photo 4.7 **River Yarrow at Philliphaugh (8)**

Photo 4.8 **River Leny at Anie (4)**

Photo 4.9 River Avon at Queens Falls Amesbury (48)

Photo 4.10 River Dun at Hungerford (37)

rivers in class 1 and clearly showed signs of instability, with heavily eroded banks and depositional features further downstream. The channel may have been recently affected by a peak flow event causing it to be over-wide.

The results from the stability survey can be compared with the findings from the morphology survey Section 4 on bank characteristics. It was found that 44% of all rivers were eroding on both banks, 36% on one bank only and 20 % showed no erosion. Figure 4.20 illustrates the finding from the bank survey.

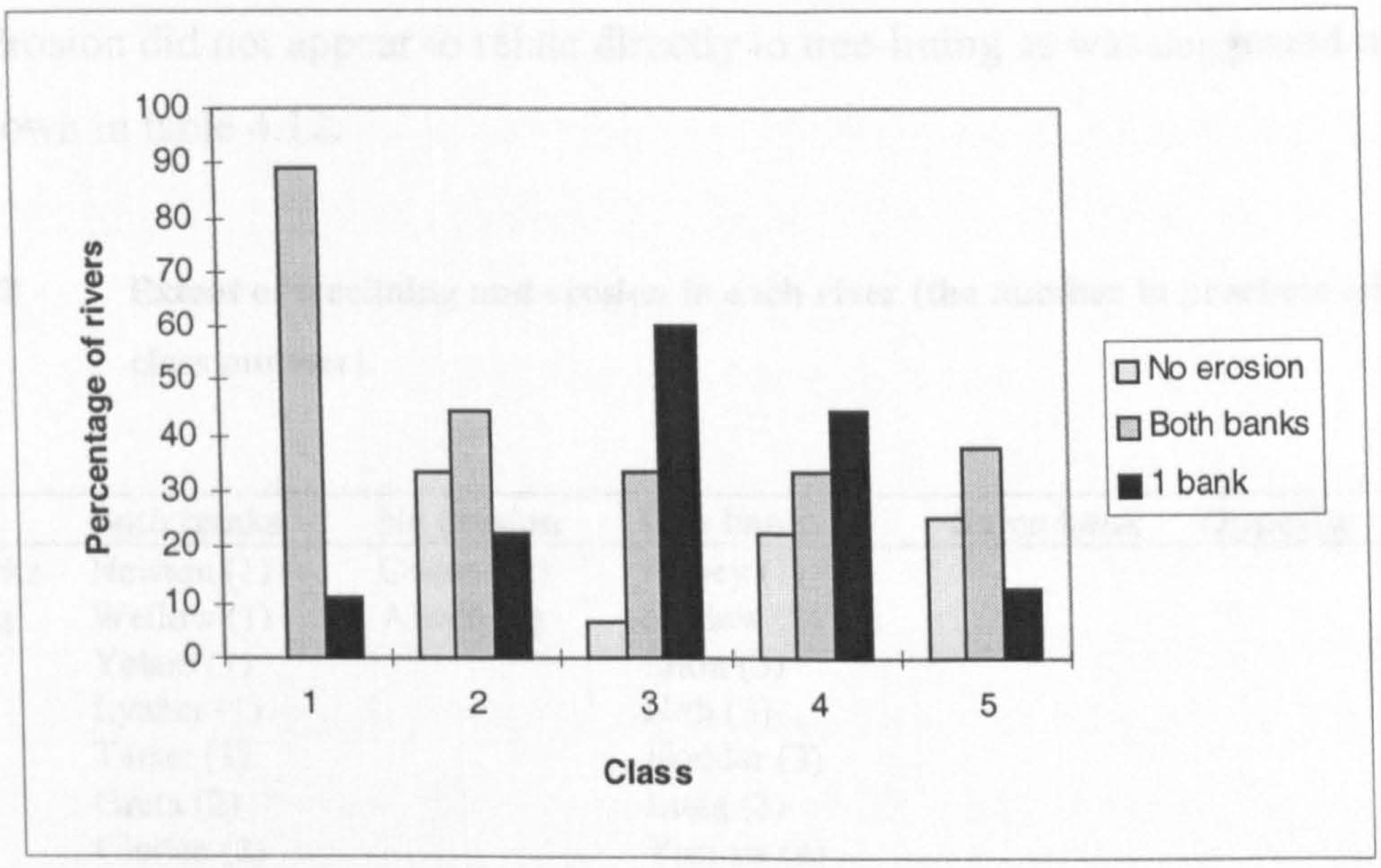


Figure 4.20 The extent of bank erosion in each class

In general, the findings correspond with the stability survey. In class 1, all rivers demonstrate bank erosion, with 90% of rivers eroding both banks. The proportion of rivers eroding in class 3 is greatest for the one bank category, indicative of lateral migration. In some cases, both banks were eroding which could imply enlargement whilst migrating, or that the channel has destabilised over the years since it was first surveyed or enlarged due to increased Qd. It was interesting to find that the highest proportion of rivers showing no erosion occurred in class 2. Although the number of channels with erosion on both banks dominates in class 2, in the stability study it was noted that in some cases erosion tended to be localised and less severe and 33% of rivers showed no process dominant, which corresponds with the findings from the bank survey.

Class 5 surprisingly showed signs of bank erosion in 50% of rivers despite the conclusion from the stability survey that no process was dominant. This highlights one of the problems of using a checklist within geomorphological surveys that allow one of two options, present or not present. Where bank erosion was observed along a reach it was recorded but no allowance was made for the age, extent or recovery of the erosional feature. It is likely that any erosion in class 5 rivers, in particular the chalk streams which have cohesive, silt clay banks, will remain evident for many years and therefore does not necessarily indicate current erosional activity.

Erosion did not appear to relate directly to tree-lining as was suggested in section 4.5.2, shown in table 4.12.

Table 4.12 Extent of treelining and erosion in each river (the number in brackets refers to the class number).

	Both banks	No erosion	One bank	Same bank	Opposite	TOTAL
Both banks treelining	Newton (1)	Coquet (2)	Fowey (1)			
	Wellow (1)	Alwen (2)	Caldew (2)			
	Yelam (1)		Ithon (3)			
	Lynher (1)		Nith (3)			
	Tarset (1)		Hodder (3)			
	Greta (2)		Lugg (3)			
	Cluden (2)		Yarrow (4)			
	Croasedale (3)		West Dart (4)			
	Rye (3)					
	Sprint (3)					
Total %	26	8	16			50
One bank treelining	Cuckmere (1)	Hindburn (3)	Exe (3)	*		
	Isla (3)	Crayke (5)	Rede (5)	*		
	Dove (5)		Ceiriog (5)	*		
			Leven (2)		*	
			Tone (3)		*	
Total %	6	4	0	6	4	20
No banks treelining	Alwin (1)	Almond (2)	Harwood (3)			
	Weaver (1)	Hebden (4)	Otter (3)			
	Usway (2)	Wylye (4)	Hebbeck (3)			
	East Dart (3)	Dun (5)	Wylye (5)			
	Derwent (5)		Snaizeholme (5)			
	Avon (5)					
Total %	12	8	10	0	0	30
TOTAL	44	20	36			

42% of rivers demonstrated signs of erosion when tree lining was present on both banks, suggesting that treelining is associated with increased erosion. However, only 8% of rivers indicate no erosion where there is no treelining, whilst 22% of rivers show erosion without treelining. The effect of treelining in some cases seems to enhance erosion, perhaps by constraining channel width but erosion also occurs where there is no treelining that could result from a lack of protection. It is also important to note that undermining of tree roots may not necessarily mean that erosion is severe and the rate of erosion in these channels may be slow.

It is difficult to quantify rivers in terms of stability on the basis of geomorphological assessments alone and for the national study it was imperative to visit as many sites as possible, ruling out the possibility of more detailed stability assessments. However, a crude stability index was developed to quantify channel behaviour and to verify the findings using a more objective method. Five indicators of incision and aggradation were used in the stability checklist and indexed as follows: signs of erosion were given a score of 1 and summed to give a score from 0-5; signs of deposition were also given a score of 1, summed but then deducted from a total of 5, again giving a score from 0-5; finally, the two scores for incision and aggradation were added together to give an overall value from 0-10, ranging from deposition (0) to erosion (10). The mean score from each class was derived and the results are shown in figure 4.21.

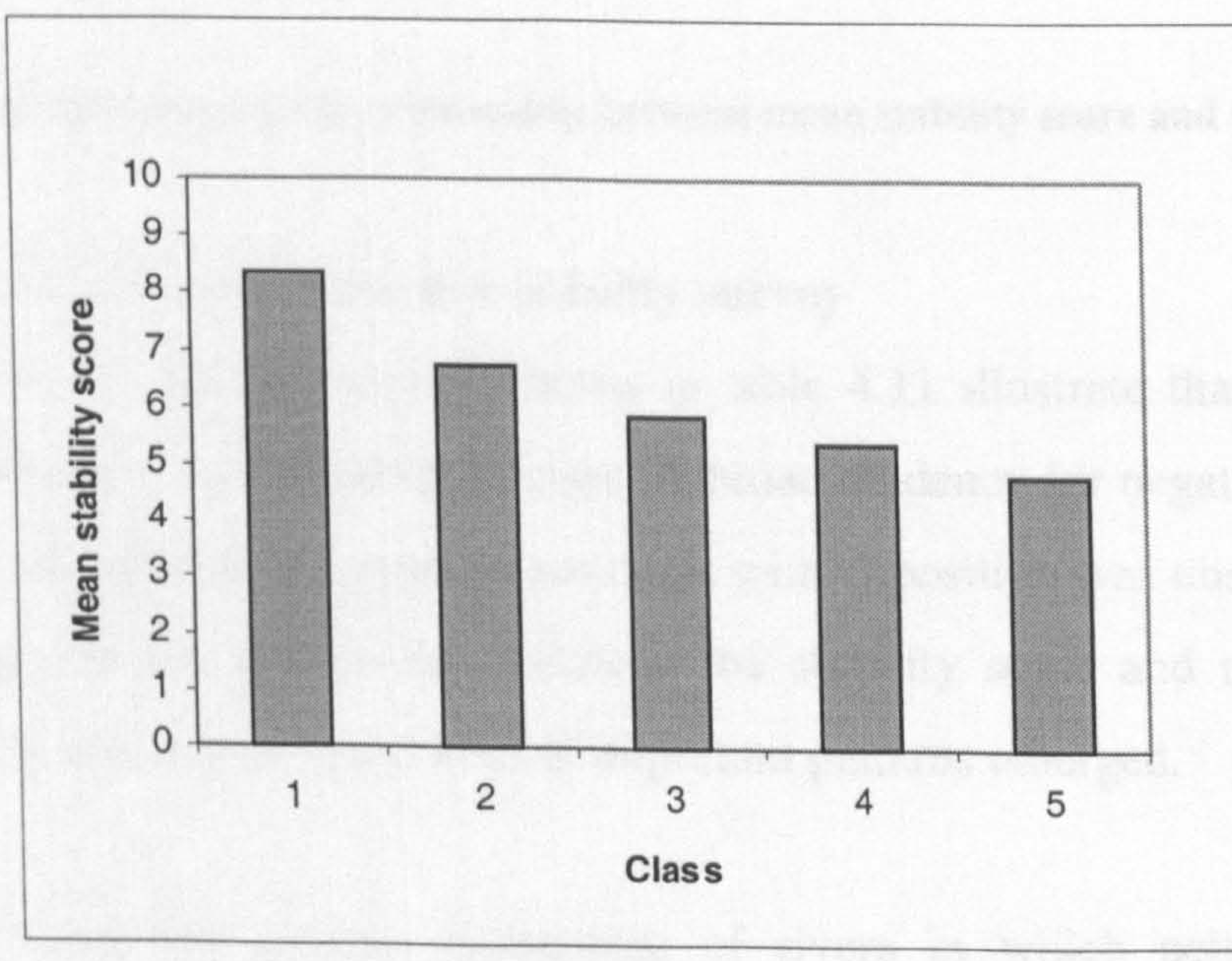


Figure 4.21 Graph showing the mean stability score for each class

The index serves as a basic measure of *relative* stability for comparison between rivers and cannot be used to indicate bed or bank stability as the parameters on which the score is based are not of equal weight. Although approximate, the scoring system is a useful method for describing channels quantitatively and allows comparison between rivers. The trend of decreasing mean scores, indicates a change from erosional to depositional processes as the residual value increases from negative to positive until class 5 where the mean score value increases from 4.5 to 5.25 indicating less activity. The relationship between the stability score and the residual values has a correlation coefficient of -0.605, confirming the direction of change, but as figure 4.22, indicates, the strength of the relationship is weaker, as a result of the cluster of extreme positive sites which are much less active than predicted.

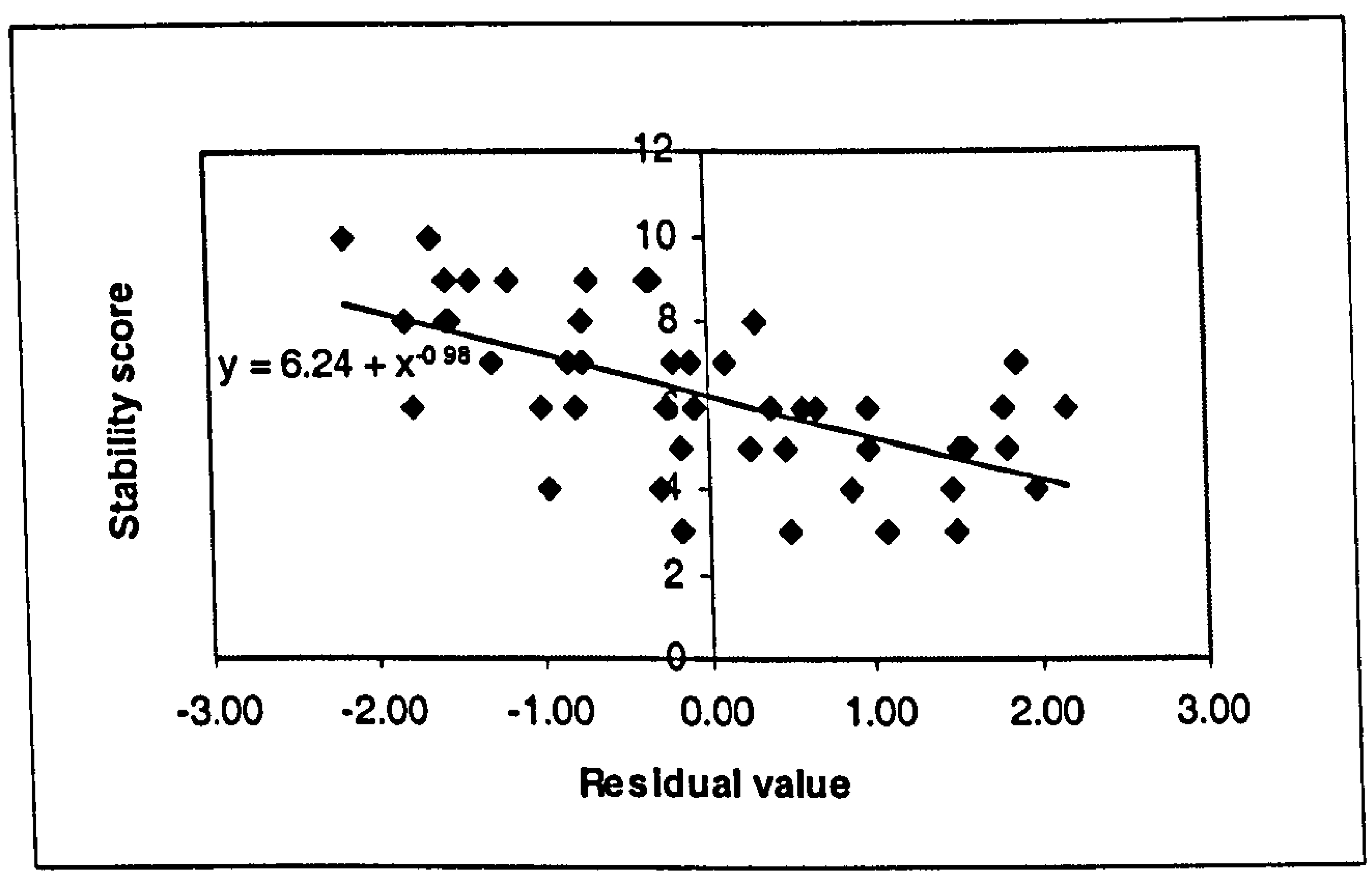


Figure 4.22 Graph showing the relationship between mean stability score and residual values.

4.5.4 Summary of results from the stability survey

The results from the stability survey shown in table 4.11 illustrate that river channel behaviour appears to vary according to class. A broad tendency for negative residuals to be associated with erosion and positive residuals with deposition was observed from the stability survey and the relationship between the stability score and residual values. However, within this overall trend several important patterns emerged.

Class 3 has the greatest percentage of rivers in which neither erosion or deposition dominate. Two types of stability were observed; inactive stability where the channel was showed no geomorphologcial activity and retained stable channel dimensions; and active stability or lateral migration, where the channel was translating planform but maintaining relatively stable channel dimensions. The process of lateral migration was supported by evidence from the bank survey which showed a high proportion of rivers were eroding on one bank only, indicative of planform change (see figure 3.4). The evidence from river in class 3 supports the hypothesis that rivers represented most closely by the regression model are most stable.

In class 1, 90% of rivers demonstrated complex and widespread erosional features on the banks, also supporting the theory that rivers least represented by the model are unstable and adjusting channel dimensions through erosional activity. The channels were often deeply incised and showed signs of slumping, bank collapse and undercutting. At the other extreme however, class 5 a tendency towards deposition but with 36.4% of rivers showing no process dominant and generally stable conditions. Weed growth and silt build up were a feature of several of the chalk streams, indicating a tendency towards aggradation, although there were several erosional scars on channel banks. Rivers within this class did not demonstrate the type of instability found within class 1 and again appeared to be characterised by distinct behaviour. Class 4, rivers also representing positive residuals, showed river channel adjustment which in line with the hypothesised changes. 60% of rivers showing signs of aggradation and revegatation suggesting decreases in channel width. Finally class 2, although dominated by rivers showing signs of erosion 30-40% showed no process dominant and similar to class 5, this to show less clearly behaviour predicted by the model.

The analysis has shown that rivers with similar residual values demonstrate some patterns in terms of behaviour shown through channel adjustment and controlling factors. The influence of certain controlling factors may exacerbate any instability occurring in the stream indirectly controlling channel behaviour. The extent to which channels adjust towards the line was investigated in the temporal study.

4.6 Temporal Study

The temporal study was designed to investigate the sensitivity of river channels to change over short time-scales and assess whether hypothesised changes, based on residual values from the regression model, were supported by the field data. The hypothesis, suggesting that rivers tend towards the model line (chapter 3), was tested using data from a subset of sixteen rivers selected from the sub-set of fifty field sites (section 4.5). Changes in channel dimensions related to Qd at each of the sites selected for the temporal study were observed over a ten-year period, using data from 1987/88 and 1996-1998. The findings were then compared with residual values from the regression model (section 4.4) to investigate the extent to which the residuals represent sensitivity to change. Residual values were also calculated for 1996-98 data, using equation (1) derived from the regression model, to examine changes in residual values through time, related to river stability (based on the findings from the geomorphological survey, section 4.5). The purpose of the temporal study was not to detail specific morphological changes at each site in order to produce estimates of the rate of change, but to investigate the magnitude and direction of river channel adjustment and identify whether the changes can be associated with varying residual values. The sensitivity of rivers to change will be assessed in relation to residual values.

4.6.1 Selection of sites for the temporal study and data quality

To minimise the effects of measurement error on the results, only sites with the highest quality geometric and discharge information were selected for use in the temporal study. It was important for the re-survey of channel dimensions to identify the exact location of the reach, made possible by Wharton's (1989) field notes which give detailed information concerning the location of the study reach in relation to the gauging station. Hey and Thorne's (1989) sites were excluded from this stage of research because it was difficult without detailed field notes to identify the exact location of the reach for re-survey.

The other major criterion for the selection of sites for the temporal study was the availability of flow records up to 1996-98 for the calculation of Mean Annual Flood (Q_{maf}). Mean Annual Flood was used as the reference discharge (Qd) for sites in the temporal study for consistency with Wharton (1989). Qd values were calculated from the updated annual maximum series held at the Institute of Hydrology. For most sites, the annual maximum data had been analysed at the Institute of Hydrology up to 1994 for the new Flood Studies Report (Flood Estimation Handbook, 1999). However, the remaining two years had not been included and highest instantaneous monthly flows were obtained for all sites for these years. The records were then carefully analysed to check for any anomalies that were then discussed with the Institute of Hydrology. Where queries remained, regional offices of the E.A. were contacted to check whether the rating curve remained accurate and whether there were any specific problems at the site. Where flow records were not available or the gauging station had closed since the sites were first measured, the sites were not included.

The cross-sectional data were obtained using the field survey methods outlined in section 4.5.3 based on Wharton (1989) to minimise variability resulting from measurement error. The representative variables were average values based on the three cross-sections surveyed at each site. Where the location of the site or the active bankfull level were in question, the site was not included in the temporal study. Sixteen sites were chosen for the temporal study, shown in table 4.13. The following section will discuss the results from the temporal study comprising changes in bankfull width related to Qd, the adjustment of other channel dimensions in relation to bankfull width and changes in residual values through time, to assess the extent to which the hypothesised changes towards the regression line are occurring.

4.6.2 Changes in bankfull channel dimensions

The overall pattern of bankfull width shown in figure 4.23 appears to broadly reflect the changes hypothesised in the model. Width increases dominate in classes 1 and 2 and width decreases dominate in classes 4 and 5. Rivers with the highest positive residuals in class 1 all show an increase in average bankfull width, with the highest in the River Yealm (65), which increased by 10.9 % from 7.95 m to 8.82 m. In class 2, changes in width were small, with negligible decreases in the Rivers Almond (5) and Greta (23), and an increase of 3.2% in the River Cluden (118). The River Coquet, showed a greater increase of 8.1 %. Overall, the rivers in class 2, were either increasing in width or showing no significant change. In contrast residuals in class 4 of a similar magnitude but negative, showed decreases in channel width of between 4 and 14 %, the greatest in the Hebden Water. The most extreme negative residuals, in class 5 were the Rivers

4.13 Data for the temporal study

River	ID	Width (m)			Discharge (m^3s^{-1})			Mean depth (m)			Capacity (m^2)			Residual (%)		
		A	B	Change %	A	B	Change %	A	B	Change %	A	B	Change %	A	B	Change %
Fowey	66	13.97	14.21	1.72	96.30	51.40	-46.63	1.37	1.10	-19.71	18.86	16.16	-2.70	-1.64	-0.79	-0.85
Weaver	90	8.15	8.50	4.29	23.79	21.91	-7.90	1.33	1.18	-11.28	9.63	9.02	-0.61	-1.55	-1.34	-0.21
Yealm	65	7.95	8.82	10.94	21.08	23.19	10.01	1.34	1.19	-11.19	10.05	11.34	1.29	-1.8	-1.34	-0.46
Camel	67	12.92	13.52	4.64	60.53	71.90	18.78	1.39	1.71	23.02	18.67	23.31	4.64	-1.4	-1.50	0.10
Almond	5	8.60	8.50	-1.16	17.14	18.77	9.51	0.67	0.79	17.91	5.66	7.16	1.50	-0.99	-1.10	0.11
Coquet	14	19.06	20.60	8.08	119.67	114.07	-4.68	1.17	0.94	-19.66	21.67	19.97	-1.70	-0.96	-0.71	-0.25
Greta	23	16.49	16.42	-0.42	72.77	75.08	3.17	0.98	1.01	3.06	15.66	16.99	1.33	-0.83	-0.87	0.04
Cluden	118	21.50	22.19	3.21	128.26	120.89	-5.75	1.42	1.29	-9.15	30.33	28.20	-2.13	-0.74	-0.55	-0.19
Harwood Beck	94	14.50	12.70	-12.41	36.67	34.40	-6.19	0.66	0.53	-19.70	9.11	6.62	-2.49	-0.29	-0.63	0.34
Lugg	73	14.25	15.29	7.30	30.37	28.99	-4.54	0.76	0.91	19.74	10.10	13.92	3.82	-0.08	0.24	-0.32
Crayke	102	13.70	12.46	-9.05	18.54	20.46	10.36	0.68	0.71	4.41	8.57	8.81	0.24	0.5	0.08	0.42
Hebden Water	27	12.3	10.56	-14.15	13.49	13.49	0.00	0.62	0.80	29.03	7.47	8.53	1.06	0.58	0.08	0.50
Leny	4	29.4	28.16	-4.22	82.02	96.69	17.89	1.04	1.35	29.81	29.27	36.34	7.07	0.98	0.63	0.35
Dun	42	8.63	8.92	3.36	2.10	2.38	13.33	0.38	0.54	42.11	3.27	4.08	0.81	2.17	1.97	0.20
Whitewater	40	6.10	5.58	-8.52	0.92	1.20	30.43	0.4	0.38	-5.00	2.29	2.14	-0.15	1.8	1.34	0.46
Avon	48	18.8	18.41	-2.07	10.41	13.07	25.55	1.37	1.24	-9.49	24.89	23.04	-1.85	1.81	2.05	-0.24

Notes

A : Measured 1987-1988
B : Re-measured 1996-1998

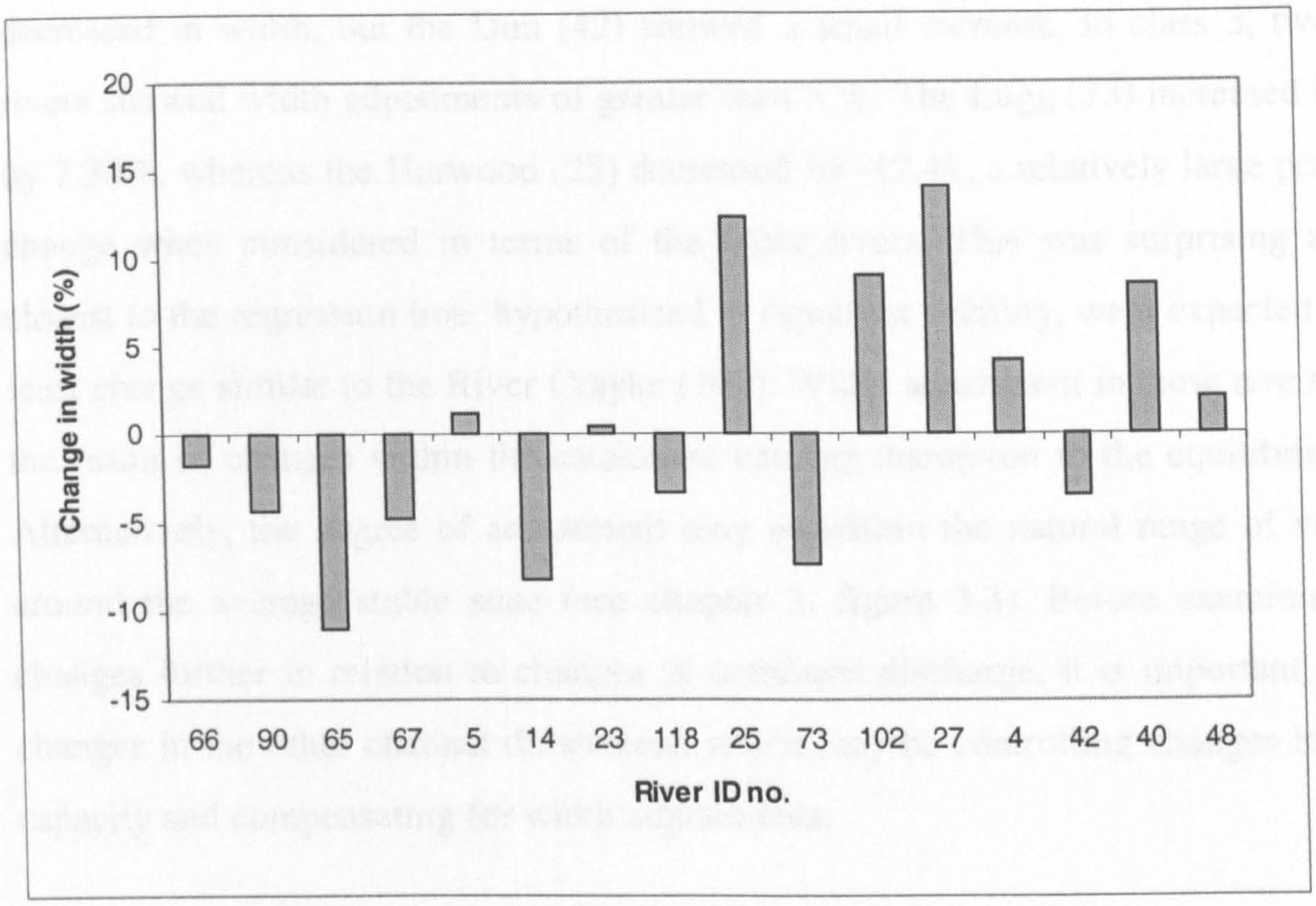


Figure 4.23 **Changes in width in each river**

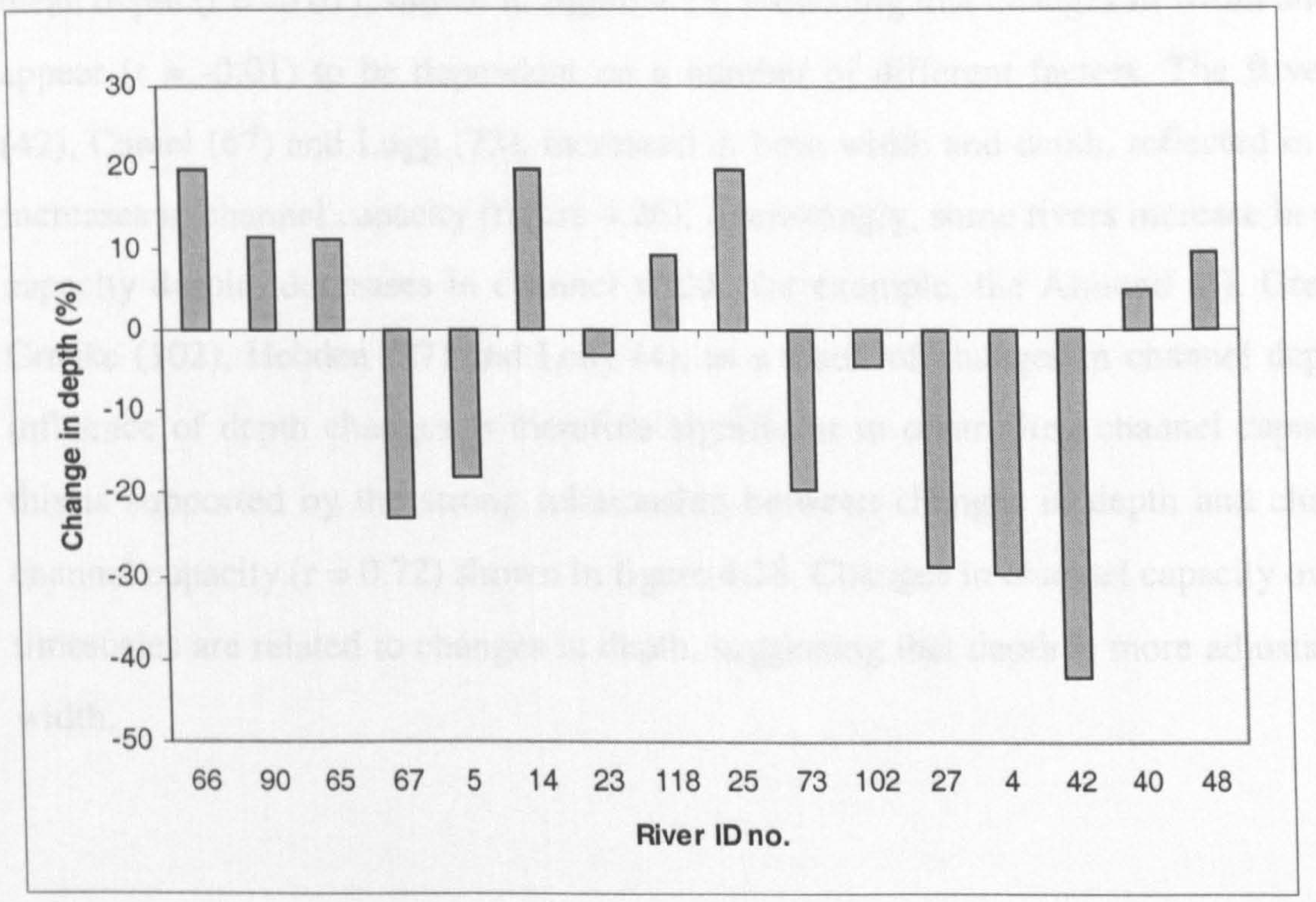


Figure 4.24 **Changes in depth in each river**

Avon (48), Dun (42) and Whitewater (40). Both the Avon (48) and Whitewater (40) had decreased in width, but the Dun (42) showed a small increase. In class 3, two of the rivers showed width adjustments of greater than 5 %. The Lugg (73) increased in width by 7.30%, whereas the Harwood (25) decreased by -12.41, a relatively large percentage change when considered in terms of the other rivers. This was surprising as rivers closest to the regression line, hypothesised to represent stability, were expected to show least change similar to the River Crayke (102). Width adjustment in these rivers may be the result of changes within the catchment causing disruption to the equilibrium state. Alternatively, the degree of adjustment may be within the natural range of variability around the average stable state (see chapter 3, figure 3.3). Before examining width changes further in relation to changes in dominant discharge, it is important to assess changes in the other channel dimensions which may be controlling changes in channel capacity and compensating for width adjustments.

There were no distinctive patterns in mean depth changes related to residual values (figure 4.24). Similarly, no relationship was found between changes in width and mean depth ($r = -0.01$), shown in figure 4.25, indicating that changes in width and depth appear ($r = -0.01$) to be dependent on a number of different factors. The Rivers Dun (42), Camel (67) and Lugg (73), increased in both width and depth, reflected in overall increases in channel capacity (figure 4.26). Interestingly, some rivers increase in channel capacity despite decreases in channel width, for example, the Almond (5), Greta (23), Crayke (102), Hebden (27) and Leny (4), as a result of changes in channel depth. The influence of depth changes is therefore significant in controlling channel capacity and this is supported by the strong relationship between changes in depth and changes in channel capacity ($r = 0.72$) shown in figure 4.28. Changes in channel capacity over short timescales are related to changes in depth, suggesting that depth is more adjustable than width.

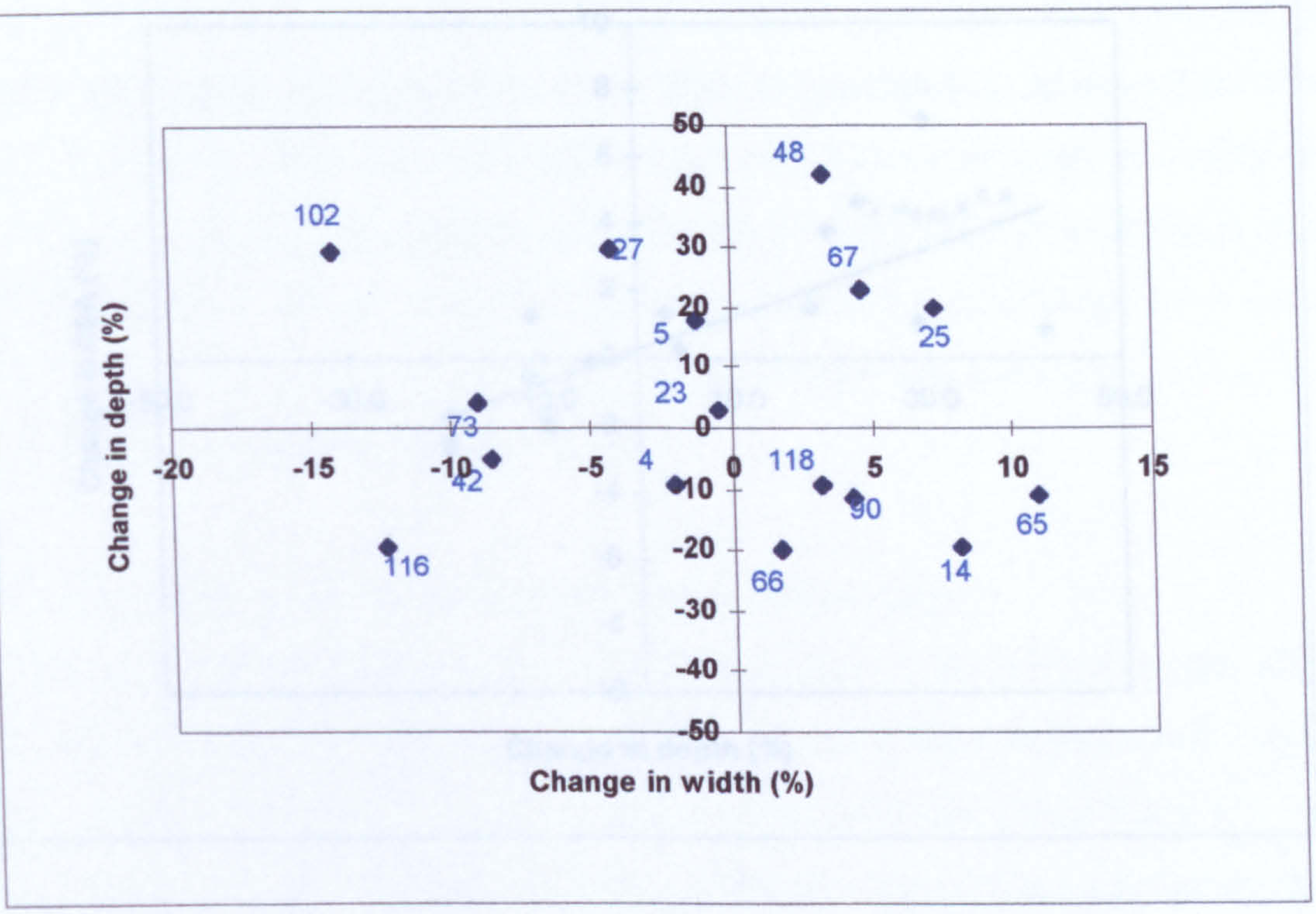


Figure 4.25 **Changes in width related to changes in mean depth**

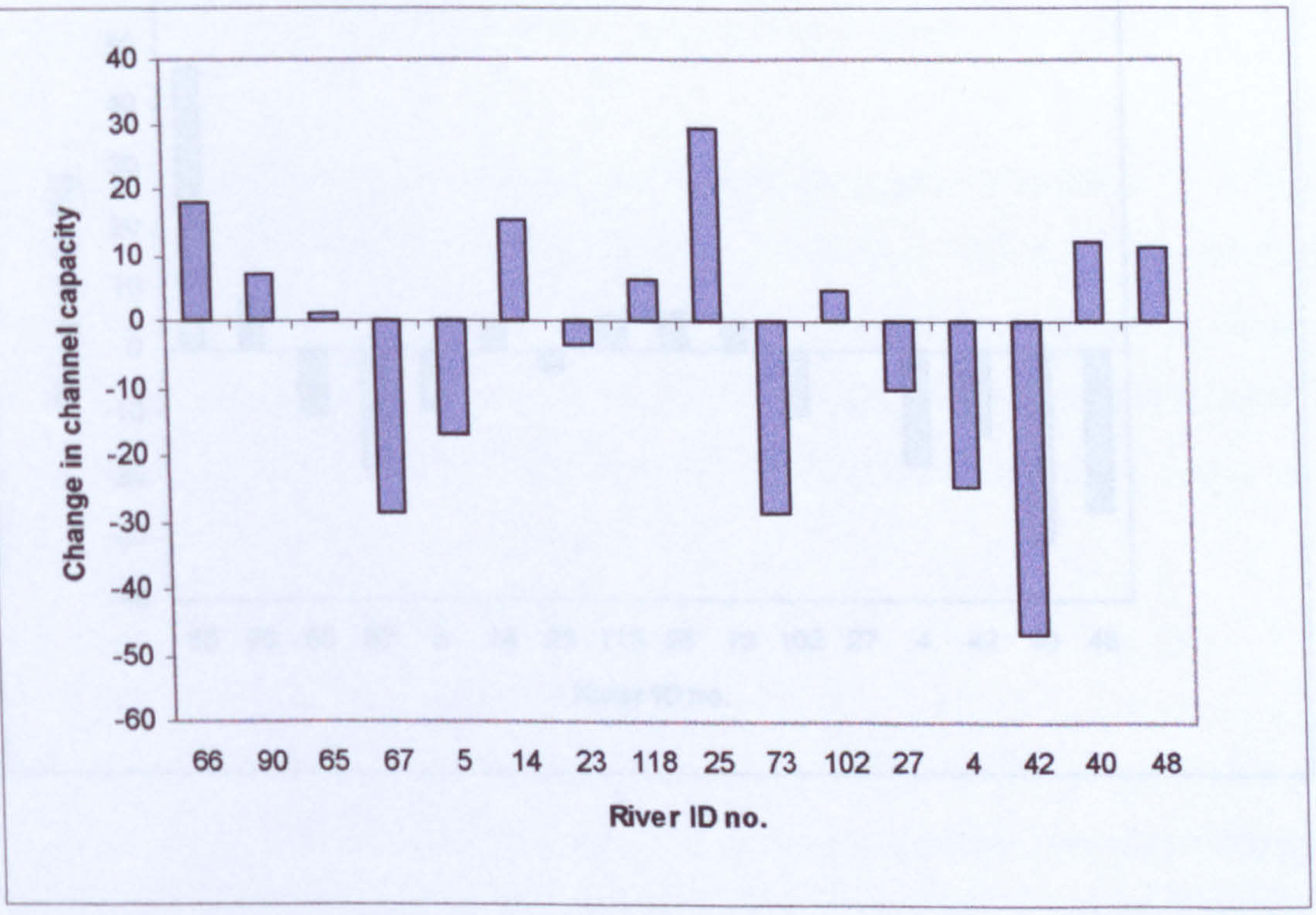


Figure 4.26 **Changes in channel capacity**

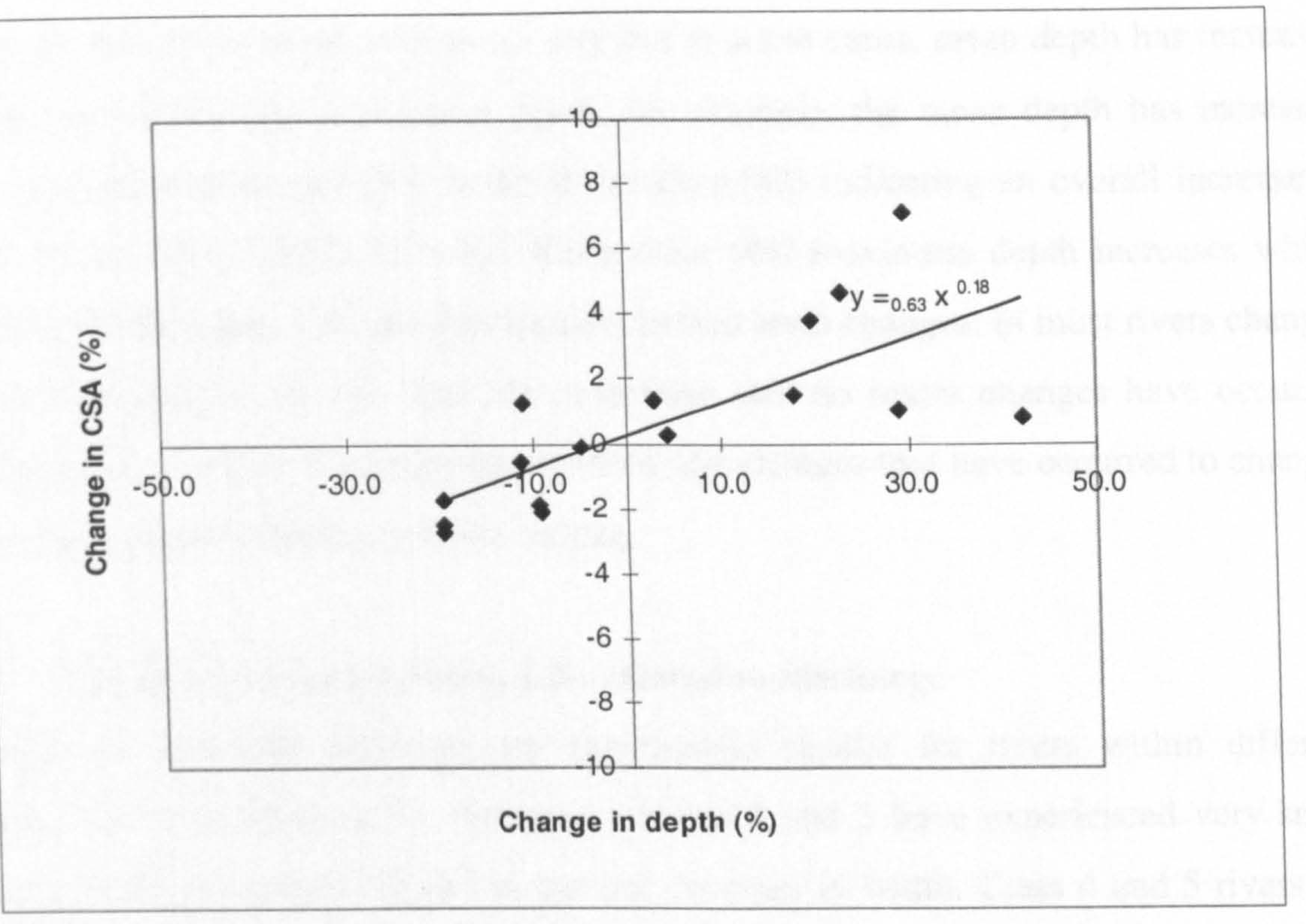


Figure 4.27 **Changes channel capacity related to changes in mean depth**

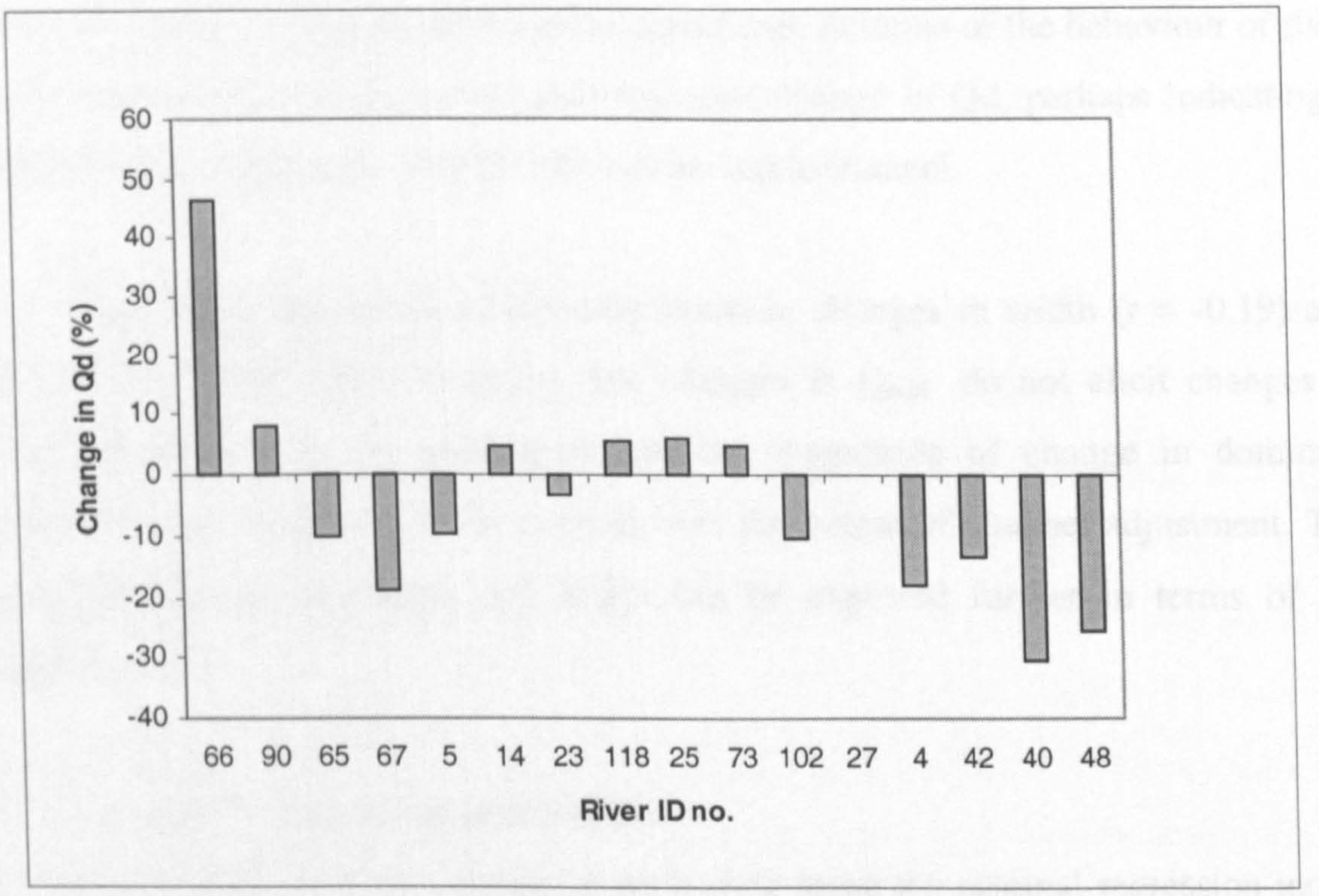


Figure 4.28 **Changes in discharge in each river**

Mean and maximum depth tend to co-vary but in some cases, mean depth has increased or decreased more than maximum depth, for example, the mean depth has increased more than the maximum depth in the River Dun (42) indicating an overall increase in depth. In the River Yealm (65) and Whitewater (40) maximum depth increases whilst mean depth decreases, indicating variability in bed level changes. In most rivers changes in channel capacity are less than 5% indicating that no major changes have occurred over a ten-year period. It is important to relate the changes that have occurred to changes in discharge and changes in residual values.

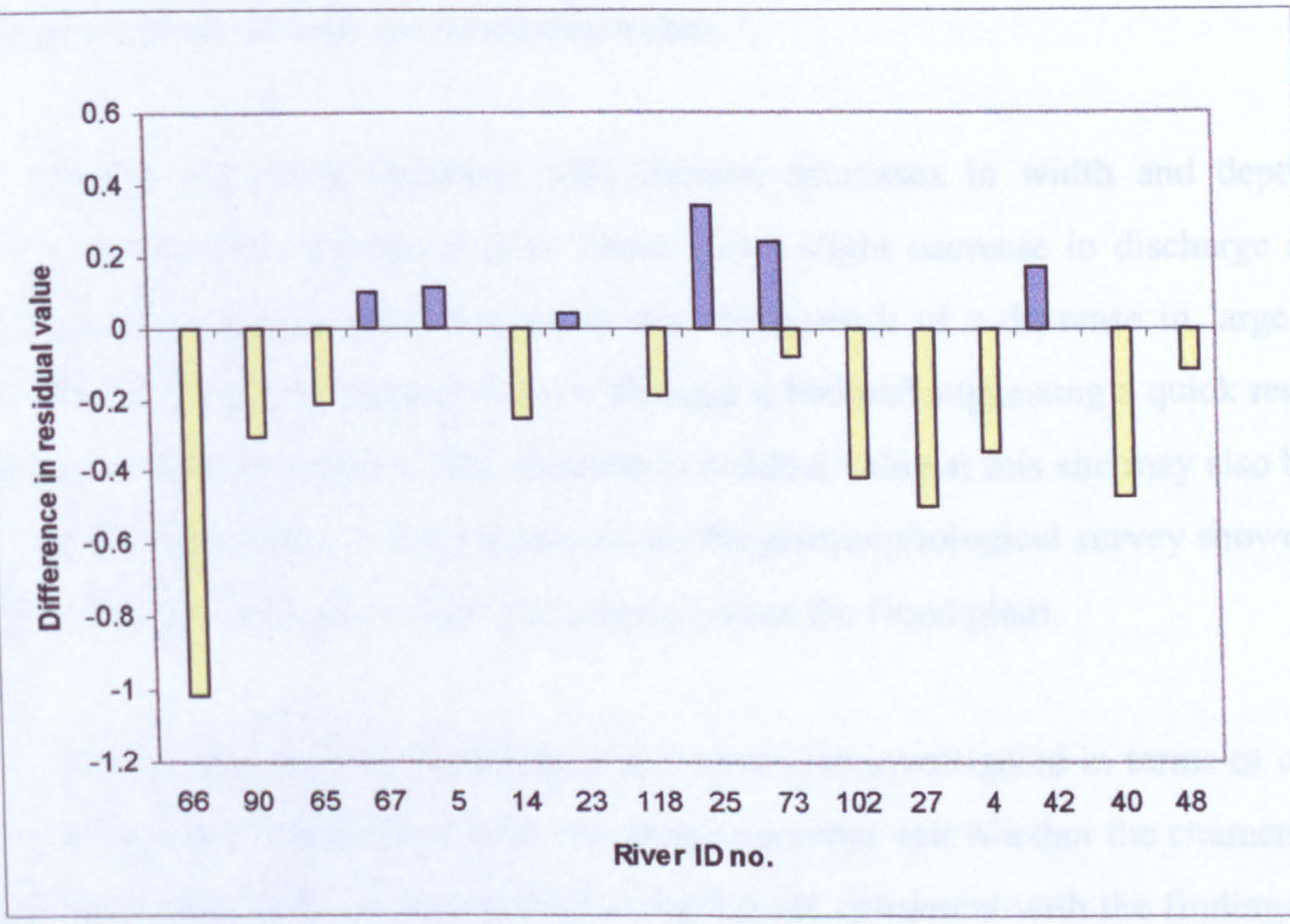
4.6.3 Changes in channel dimensions related to discharge

Changes in dominant discharge are surprisingly similar for rivers within different classes, shown in figure 4.29. Rivers in classes 2 and 3 have experienced very small changes in Qd of around 5% and in general decrease in width. Class 4 and 5 rivers are dominated by increases in Qd of over 10%, excluding Hebden Water (27) where there is no change in discharge. The greatest variability in changes was found in class 1 where the Weaver (90) and Fowey (66) decreased in discharge and the Yealm (65) and Camel (67) both increased. These patterns may be significant in terms of the behaviour of river channels with lower residual values showing least change in Qd, perhaps indicating a less variable flow regime associated with a more stable channel.

There is no significant relationship between changes in width ($r = -0.19$) and depth ($r = 0.31$) with Qd, illustrating that changes in Q_{maf} do not elicit changes in channel geometry over the short term and the magnitude of change in dominant discharge does not appear to be associated with the extent of channel adjustment. The relationship between discharge and width can be explored further in terms of the residual values.

4.6.4 The significance of residual values

New residual values were calculated for each river using the original regression model ($n = 124$) (section 4.3.3). Q_{maf} values obtained from updated flow records to the time of measurement were used as the independent variable to predict bankfull width. The difference between the predicted width and the average bankfull width derived from field surveys carried out during 1997/8 for each of the 16 sites, was transformed into a standardised residual value using equation 4.5. The new residuals were compared with the original residuals from the 124 sites to assess the direction of change and evaluate whether river channels had moved closer to the regression line within the subset of 16 rivers (shown in figure 4.30). 75 % of rivers in the temporal study have decreased in residual values, indicating a tendency for rivers to move closer to model line. The residual values increased in six rivers for several possible reasons.



4.29 Changes in residual values for bankfull width and discharge

The Rivers Dun (42), Camel, (67) and Lugg (73) all increased in both width and depth, enlarging channel capacity in all three rivers. The River Camel (67) and River Dun (42) both showed increases in discharge which contribute to the increased residual value. The River Camel (67) is under-wide in relation to discharge and thus any increase in discharge despite associated enlargement of the channel evident from survey data and the stability survey which indicated erosional processes were dominant, resulted in an increase in the residual value. At the other extreme, the River Dun (42) is over-wide, and continues to enlarge with increasing discharge. However, as suggested in section 4.5, this channel may be adapted to a different base flow and is therefore simply adjusting to an increase in Q_{maf}.

In comparison with these rivers which have enlarged, the River Greta (23) and River Almond (5) have shown very little change, with a decrease in width of only 0.1m in both rivers over the ten year period despite increases in discharge in both rivers. The River Almond showed a 19.71% change in depth indicating that the channel has adjusted its channel capacity by incising, but the River Greta showed vary little change in depth. Already under-wide, these channels remain unchanged and the increase in discharge results in an increase in residual value.

Finally, the River Harwood (25) showed decreases in width and depth and moved away from the regression line. There was a slight decrease in discharge at this site and the decrease in width and depth may be a result of a decrease in large flood events. The channel is an upland river, with large a bedload suggesting a quick response to changes in the flow regime. The increase in residual value at this site may also be part of the oscillation around a mean condition as the geomorphological survey showed that this river was dynamic and actively migrating across the flood plain.

The changes in residual values rivers were also investigated in terms of class to assess whether they had shifted from one class to another and whether the characteristics of each class observed in the sections 4.4 and 4.5 are consistent with the findings in the temporal study. Although the class divisions are arbitrary, they are used as a way of grouping rivers according to residual values and, as with any classification system necessarily impose boundaries which divide rivers which are similar. The proximity of the river boundaries between classes must therefore be taken into consideration.

In the extreme classes, most rivers remained within the same class, particularly in Class 5 where there was no change. The Hebden Water (27) moved down a class from class 4 to 3 demonstrating a close relationship between Qd and width. The River Fowey (66) changes from class 1 to class 2 and the evidence from the stability survey supports the changes observed in bankfull width. It is suggested that this river may have crossed an intrinsic threshold within the system.

Although the temporal study is only representative of 16 rivers sites it has strongly confirmed the hypothesis that rivers are progressing towards the model line but also highlighted the diverse interactions between the independent and dependent variables. 75% of rivers showed a decrease in residual value illustrating a tendency towards deviance around the model line. However, several rivers in class 3 moved away from the model line although did not change class indicating that stability over a ten year period may be a transient trend. However, it could also be oscillation around a mean value and there is no data to indicate the time-scales of adjustment. This may be an area for further investigation. The temporal study also highlighted the importance of depth adjustment in relation to channel capacity and the width residual value. It is clear that the interaction between width and depth is important in determining the dominant mode of adjustment and likely direction of change.

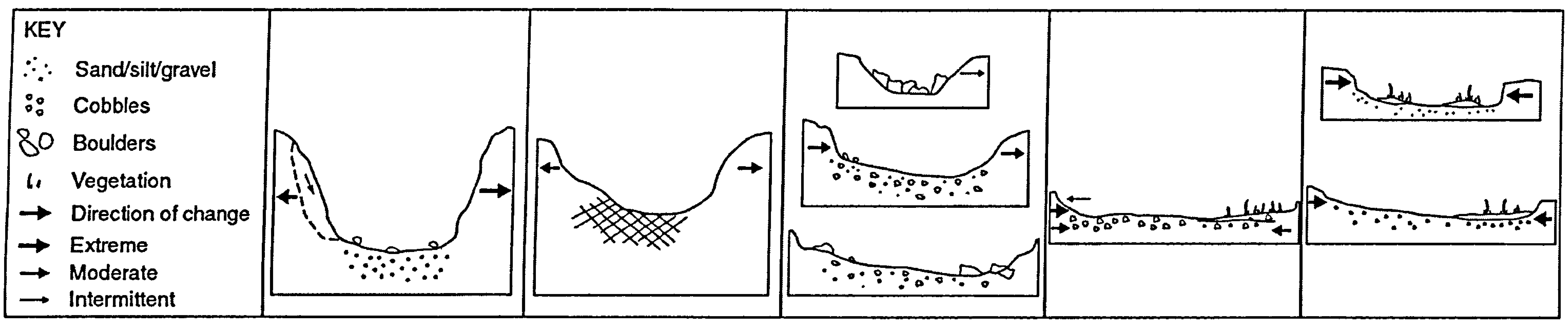
4.7 Summary

The analysis of the geometric and hydrometric properties of rivers in each class proved to be useful in assessing whether residuals were indicative of geomorphologcially distinct river morphologies. The geomorphological characteristics of rivers were found to vary in each class. Class 3 contained a wide range of rivers in terms of channel geometry and discharge. The widest channels were found in class 4 compared with class 1 rivers that had the lowest mean width and a relatively small range, despite a large variability in Qd values. The residual values in both classes were wide ranging and associated with high standard deviation values suggesting that rivers are responding to a wide variety of controlling factors which could be resulting in instability. Class 5 rivers showed a consistent under-prediction by the model and this could be related to the use of Q_{maf} to predict channel dimensions which are actually adjusted to a discharge with a much longer return period.

The findings from the field study demonstrated that some of the variability within downstream hydraulic geometry models is dependent upon environmental controlling factors, in particular, the independent variable Qd and underlying geology. Chalk streams in the south east of England predominate in class 5. These rivers are characterised by baseflow conditions and could be adjusting to a bankfull discharge with a much higher return period than the mean annual flood. Class 2 also appears to be influenced by a specific controlling factor: bedrock, and has a narrow range of residuals suggesting that the relationship between channel geometry and discharge is influenced by a common controlling factor. In general however, it was difficult to associate individual controlling factors with rivers of different residual values.

Table 4.14 **Characteristics for rivers in each class and diagrammatic examples**

Characteristics	Class 1 (>1.0)	Class 2 (-1.0 to –0.5)	Class 3 (-0.5 to 0.5)	Class 4 (0.5 to 1.0)	Class 5 (1.0)
Mean width m (range)	11.06 (25.45)	13.50 (17.85)	20.35 (50.05)	28.86 (48.20)	25.32 (51.70)
Mean Qd m^3s^{-1}(range)	59.69 (378.99)	54.91 (143.31)	95.74 (734.18)	120.36 (416.90)	59.69 (235.92)
W:D ratio (range	7.96 (12.42)	10.43 (15.72)	13.00 (30.14)	12.74 (13.78)	15.07 (23.15)
Predicted width	Under-wide by 2.72 to 13.07m.	Under-wide by 0.97 to 6.28m	Under-wide by up to 3.67m; over-wide by up to 6.05m.	Over-wide by 1.67 to 13.74.	Over-wide by up to 23.29m.
Bed Materials (fieldsurvey)	No characteristic bed material types. Contains silt, sand and gravel bed rivers.	Bedrock dominated .	Mixed bed material or cobble bed.	No dominant bed material. Boulder bed channels.	All bed material types, representative of silt/sand/gravel bed rivers.
Bank materials (field survey)	No sand gravel banks. Highest % of silt/sand bed materials.	Dominated by clay/silt and silt sand bank rivers.	No dominant bank material	Sand/gravel banks channels most dominant.	Clay/silt banks dominate.
Stability (field survey)	90% eroding Severe erosion and slumping in some rivers. Instability in the majority of rivers.	62.5% eroding Erosion evident less severe and often localised in places.	75 % no process dominant Active or inactive stability evident. In some rivers there is lateral migration. Others no change.	40% no process dominant. 60% depositing. Deposition dominant with some rivers showing no observable change.	54.5% depositing 36.4% no process dominant Deposition in channel with little or no change in other channels.



The typical characteristics of river channels in each class based on the findings of the initial analysis and field survey are shown in table 4.14. The diagrams represent the types of cross-section found in each class and likely directions of change.

Residuals were found to be indicative of river channel behaviour and stability. Rivers in class 3, which were closest to the model line, demonstrated little or no channel adjustment and two types of stability were identified as either active or inactive which were similar to Downs' (1995b) definition of stable and lateral migration respectively and also with classifications proposed by Hydraulics Research (1992) of dynamic and moribund stability. Rivers in class 3 demonstrating stable conditions, occurred in rivers of a wide range of channel sizes and Qd. Class 4 rivers were geomorphologically distinct; wide channels all showing active signs of deposition but they could not be separated according to the particular controlling factors and showed no geographical clustering. In terms of adjustment, class 1 was the most active with signs of extreme erosion and bank slumping in several of the channels. The rivers were under-wide as shown by the model and were associated with low W:D ratios and it several different factors were identified as preventing channel width adjustment, including high silt-clay content in the bed and banks, responsive flow regimes and vegetation.

The temporal study highlighted the importance of comparing changes in width with other channel dimensions to assess changes in channel morphology. The regression model was based on the relationship between width and discharge and it is important to consider the interaction between width and depth in controlling channel capacity (A_b) and efficiency (R). There was no significant relationship between width and depth changes, but changes in channel capacity were strongly related to mean depth showing that changes in depth influence channel form. It was found that some rivers increased in A_b despite decreases in channel width and the influence of depth is therefore crucial to understanding changes in cross-sectional form downstream. Although the residual values for width - discharge relationships may be high magnitude, adjustment of channel depth may partly explain the variability, either as a cause where depth is the more adjustable variable and width remains static in relation to Qd or a response, where depth is adjusting to compensate where width is not adjusting. This will be investigated further in the catchment study which will assess adjustment at a reach in terms of changing channel geometry downstream throughout the catchment.

CHAPTER 5

THE CATCHMENT SCALE

"The major task for applied fluvial geomorphologists, is the elucidation of the patterns of spatial variability of channel geometry in various environmental settings and the identification of the scale at which individual environmental processes operate to control channel geometry"

(Ebisemiju, 1991, p.31-32)

5.1 Introduction

Chapter 4 focused on variability of channel geometry - discharge relations between rivers from a range of environments across the UK. This chapter reports on the variability in channel geometry within the same river system, to assess the extent to which changes in channel geometry downstream can be used explain river channel adjustment and stability at the reach scale. There are three main objectives within this overall aim (Table 5.1).

Table 5.1 Research objectives for the catchment study

- To investigate changes in channel geometry downstream
- To assess river channel stability in relation to the adjustment of channel geometry
- To establish whether there appear to be any dominant controls on channel geometry - discharge relationships

The chapter begins by describing how the study catchments were selected (5.2), the main characteristics of each catchment (5.3) and the location of sites downstream along each of the rivers (5.4). This is followed by the fieldwork methodology (5.5), which includes a detailed description of the compilation of the geomorphological survey, designed to gain as much detail as possible about each site. The results (5.6) were structured according to the research aims and drawn together in the synthesis and summary (5.7).

5.2 Selection of the study catchments

The underlying strategy when selecting the catchments was to choose three contrasting river systems to allow a comparison of geomorphological processes operating in different environmental conditions. Three catchments were chosen so that comparisons could be made between rivers in different environments based on detailed downstream field investigations. The catchment study focused on the downstream changes within a river system and the purpose of the field study was therefore to obtain detailed information about changes in a small number of catchments as opposed to the national study which looked at variability on a broad scale between a large number of rivers. It was proposed that the catchments chosen should consist of: one low energy river in the south of England, the environment where restoration is most often required in the UK; an active gravel bed river in an upland, high energy environment; and a catchment containing a river with segments of contrasting environmental characteristics.

The term catchment, for the purpose of this research, refers to the catchment area above the gauging station used as the final site for measurement. Initially, it was intended that catchments with a network of gauging stations should be chosen for study to allow downstream channel geometry-discharge relations to be developed using flow data. The original proposals, based on maps illustrating the locations of gauging stations in the Hydrometric Register (Marsh and Lees, 1993), included river catchments such as the Don, Allt Deveron and Dee in North East Scotland, the Medway in Kent and the Yorkshire Derwent, that all had a series of gauging stations located throughout the catchments.

However, preliminary investigations into the viability of undertaking research on this scale, illustrated that rivers with catchment areas of this size would be impossible to survey, because the channel size and discharge would be too large. It was necessary to select rivers with smaller catchment areas despite the resulting loss of gauging station networks. Sub-catchments forming part of larger river networks were considered and the gauging station at the furthest point downstream in the catchment was used as the final reference site. It was decided that the rivers should *not* be selected from the main national database (124 sites) to allow the hypotheses and conclusions from the national study to be tested using data from the catchment study. To guide the selection procedure a list of criteria were developed based on the findings of the initial search, shown in table 5.2.

Table 5.2 **List of criteria used to select rivers for field investigation.**

1. The catchment must contain a gauging station with a flow record of at least ten years and a consistent and reliable stage discharge relationship.
2. The flow regime of the catchment must be as natural as possible and must not be affected by the operation of reservoirs, major abstractions, artificial flow regulation.
3. The river channel must be in a semi-natural condition (defined in table 3.2) and accessible at as many points as possible throughout the catchment.

The lowland catchment was the first to be selected and a short list of six semi-natural river systems falling within the scope of these criteria was compiled, from which the study catchment was eventually chosen. The final selection process was based on detailed information about each catchment obtained from 1:25000 maps, EA sources and where possible field investigations to ascertain the suitability of possible study sites downstream.

The initial field investigations were undertaken in the south east of England to find a lowland river representative of the type of rivers likely to be restored (New Rivers and Wildlife Handbook, 1996). The Arun, Rother, Kird, Lymington and Highland Water were all assessed at various points throughout the catchments, but could not be used for several different reasons. The River Arun was tidal at the gauging station and was too deeply incised for field survey measurement to be undertaken safely or accurately. A river channel with a catchment of this size ($379km^2$) was too large. The River Rother was relatively natural but there were problems of access at the gauging station that was also the site of a waterworks, and upstream there was some evidence of channelisation. Access was also a major problem for the River Kird due to extensive private landownership. The river at the gauging station could not be accessed, but when the channel was observed slightly further upstream, it was found to be too small (catchment area $66.8km^2$) and overgrown. The Lymington and Highland Water, used for geomorphological research in the past, were fully investigated in the field, but finally rejected on the basis of the impact of land management and tourism on the river channel observed at many of the sites in the New Forest and the presence of a large amount of coarse woody debris which made identification of the bankfull level difficult. The River Windrush in the Thames valley was selected as a representative lowland river, with negligible disturbance to the natural flow regime upstream of the gauging station, good access and very little impact on the channel at the sites investigated.

The selection of the remaining two catchments took into account the findings from the preliminary fieldwork which indicated that catchments larger than $300km^2$ and smaller than $80km^2$ would be unsuitable for study. The North Yorkshire Moors and the Lake District were investigated for possible catchments with a varied topography including upland and lowland segments and after detailed map and field investigation the River Seven was selected, originating in moorland conditions, flowing out of the North Yorkshire Moors and onto the Vale of Pickering. The final river selected for study was the River Livet, Grampians, Scotland, a high energy, pristine, semi-natural river. The three catchments are described more fully in section 5.3.

5.3 Catchment descriptions

The three catchments chosen for study were the River Windrush, Gloucestershire; the River Seven, North Yorkshire; and the River Livet, Morayshire, Scotland, the locations of which are shown in figure 5.1. The catchments are characterised by different environmental conditions, the result of varying climatic and topographical controls summarised in table 5.3.

The Windrush, is a lowland catchment with a maximum altitude of 298m and the smallest mean annual rainfall (745 mm), despite having the largest catchment area. In contrast, the River Livet has the smallest catchment area ($104.0km^2$) but the highest mean annual rainfall (1011mm), falling on a catchment with a maximum altitude of 720 m. The River Seven lies between the two, with a relatively high maximum altitude 432 m and annual rainfall of 890mm, but a catchment area of 121.6 km^2 similar to the River Livet.

These differences are reflected in the drainage density (D_d) values for each catchment. Drainage density is the length of stream per unit area, a measure of fundamental importance when characterising drainage basin form, reflecting the

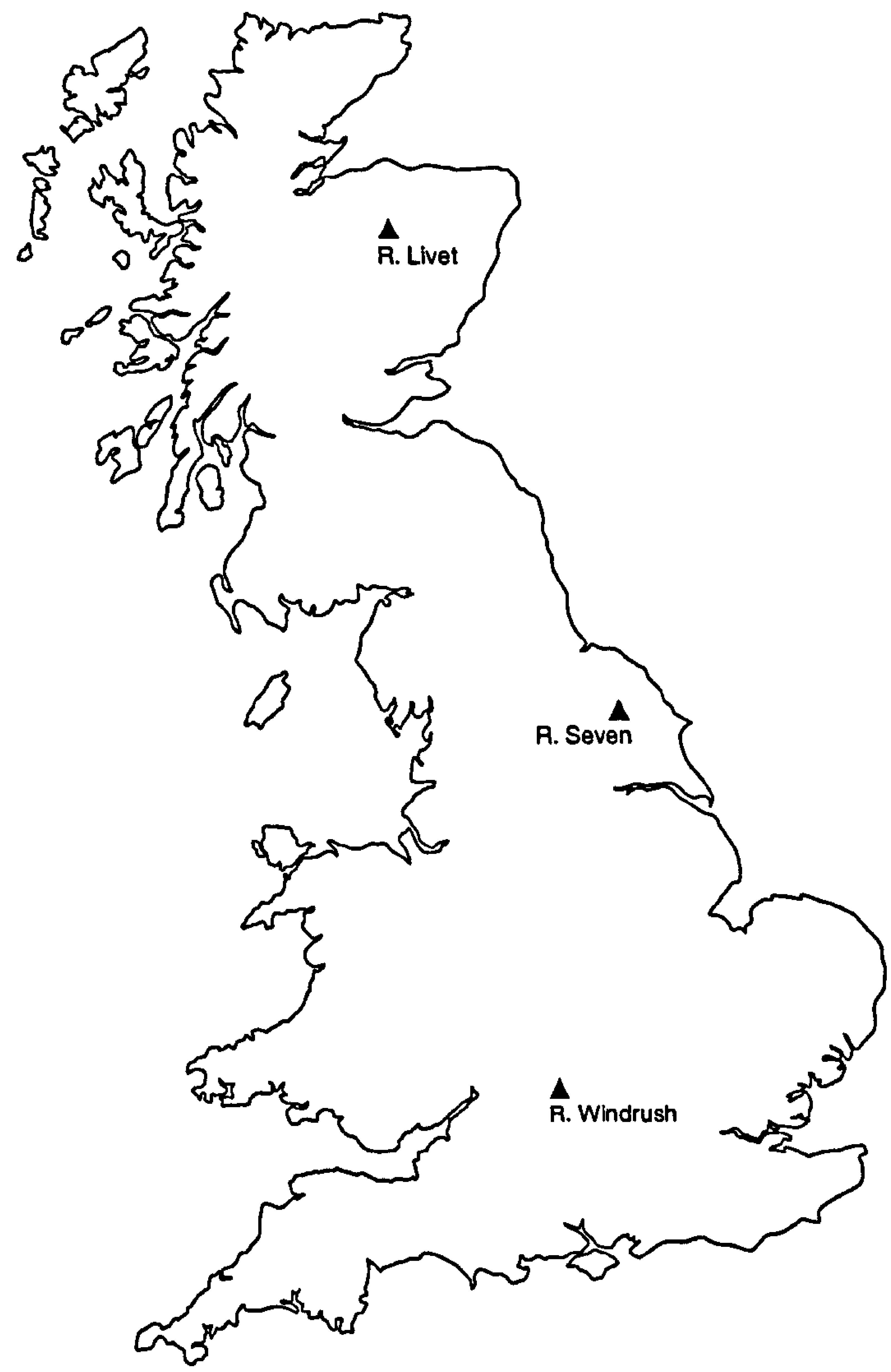


Figure 5.1 The location of the study catchments.

Table 5.3 Study catchment details

River	*Catchment area km²*	*Total Channel Length (km)*	*Distance Downstream (km)*	*Drainage Density (km km⁻¹)*	*Maximum altitude (MoD)*	*Mean annual rainfall (mm)*
Windrush	296.0	156.98	47.47	0.53	298	745
Seven	121.6	125.21	30.38	1.03	432	890
Livet	104.0	144.05	15.74	1.38	720	1011

Source: River Flow Measuring Station Information Sheets, Institute of Hydrology, Wallingford, 1998.

topographical, lithological, pedological and vegetational controls (Gregory and Walling, 1973). The Livet has the largest drainage density of 1.38 km $km^{2\ -1}$, a dense surface drainage network and rapid increase in total channel length downstream. Drainage density for the River Windrush is less than half the D_d of the Livet, explained by the geology; pervious Oolitic limestone which underlies most of the catchment, characterised by groundwater springs and drainage systems which feed the Windrush. The number of tributaries entering the stream is much smaller in the River Windrush than both of the other catchments, despite the fact that the Windrush covers the longest distance downstream. The River Seven has a drainage density of 1.03 km km^{-1} with 33 tributaries entering the stream between the source and the final site, more similar to the River Livet in morphometry than the River Windrush. On the basis of this initial overview, the catchments are described more fully in terms of their main characteristics in sections 5.3.1, 5.3.2 and 5.3.3.

5.3.1 The River Windrush

The Windrush catchment is predominantly rural, with landuse dominated by agriculture, split mainly between arable (46%) and grassland (27%) (LEAP, 1996). The catchment forms part of the eastern belt of 'Cotswold' limestone, although the river also flows over Fullers Earth Clay southern part of the catchment. The River Windrush originates in the Cotswolds, approximately 4km north of the village of Temple Guiting. The river is fed at this point from the underlying Oolitic limestones and a number of springfed tributaries. It flows south for 8km to Naunton and then in a South Easterly direction through Bourton-on-the-Water and then Burford, the main town within the study catchment. There is negligible disturbance to the natural flow regime until Worsham where there is abstraction for drinking water. The channel has been narrowed immediately after Worsham and the effects of flow regulation and narrowing may be seen at the final site at Minster Lovell downstream of the station.

5.3.2 The River Seven

The source of the River Seven is located close to Rosedale Head in the North Yorkshire Moors and from there flows south down Rosedale towards the Vale of Pickering. Rosedale is part of the Jurassic upland of, characterised by varying relief which reflects the degree of erosion of underlying sandstones, siltstones and shales. Most of the River Seven flows over Alum shales known as Serpula beds laid down during the

Photo 5.1 Rosedale

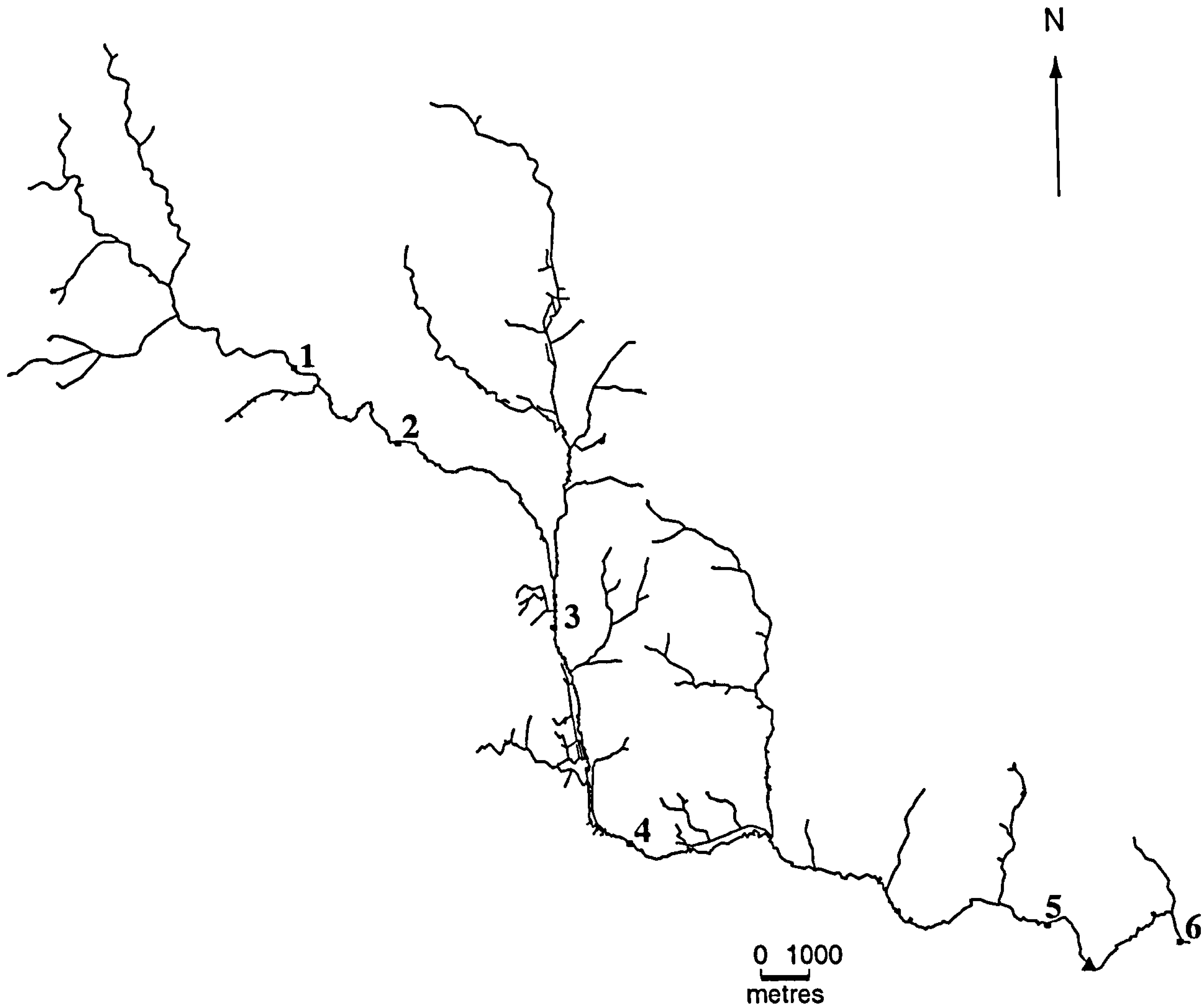
Photo 5.2 Glen Livet

Upper Lias and Rosedale East Ironstone which overlies the Serpula beds. The surrounding catchment is predominantly underlain by magnetic limestone known as the Dogger. The upland areas of the catchment are moorland and used mainly for hill sheep farming. There are two Forestry Commission forests within the catchment; Hartoft forest runs directly adjacent to the river between two of the sites. Further downstream, when the river flows out of Rosedale and onto the plains of the Vale of Pickering, arable farming predominates. The flow regime is natural but there is a loss of water underground to the adjacent River Dove that has an impact on summer baseflow, although the amount has not been quantified.

5.3.3 The River Livet

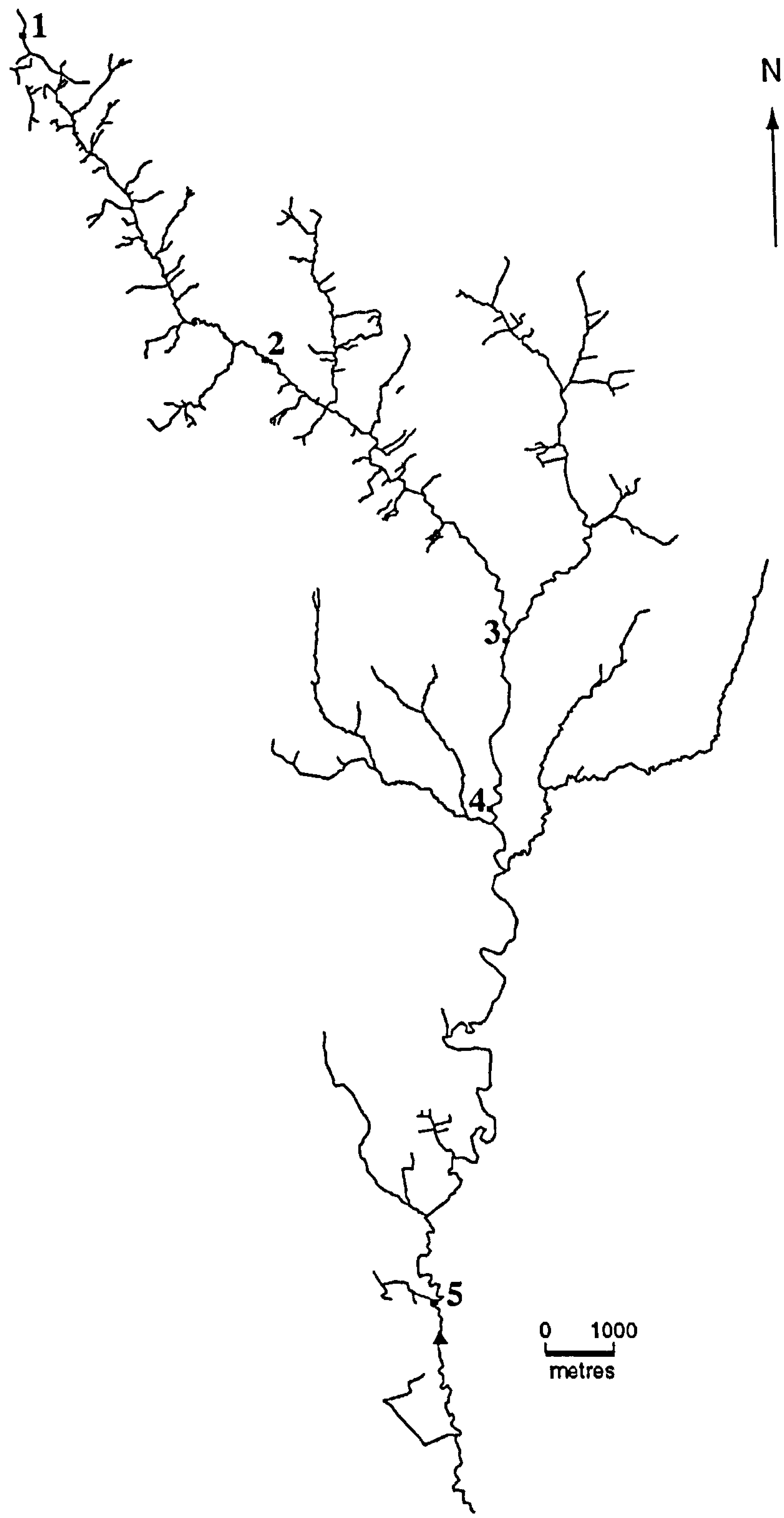
Glenlivet, the third study catchment, is located in the Grampian mountains North East Scotland (see photo 5.2). The River Livet drains a wide area encompassing the Ladder Hills in the south of the catchment and originating in the hills of Glen Suie in the North East. The river flows south down Glen Suie until the confluence with the Kymah Burn, one of several large tributaries draining the Ladder Hills, where it turns North West down Glen Livet through Tomnavoulin until the confluence with Strath Avon, the main river draining the Caringorms and eventually meeting the River Spey. No part of the catchment lies below 200m and altitude and exposure are key factors controlling vegetation and landuse.

There is a settled farming population in Glen Livet and landuse is split between moorland grouse and rough grazing 53%, forest 14%, Arable 10% and other 23% (Wells, 1998). 14 % of the land area is taken up with commerical plantation established during the 1950s-1960's by the forestry with only 500 hectares of land as semi-natural woods. There are several whisky distilleries along Glen Livet an important part of the catchment, but these have a minimal impact on the flow regime which is natural. Most of Glenlivet is underlain metamorphic Dalradian rocks - dominantly quartzites, black schists (with various quartzite and limestone bands) and pelite (shale). In the centre of the catchment from Tomintoul and Tomnavoulin Old Red Sandstone overlies these metamorphics. However, the River Livet and its tributaries from Alanreid to the Suie and up the Blye Water to Ladderfoot are underlain by the only area of granite to be found in the area (Wells, 1998). Glen Livet is a mixture of glacial and pre-glacial landforms, cut by ice and glacial meltwater. Glacial deposits on the hills impede



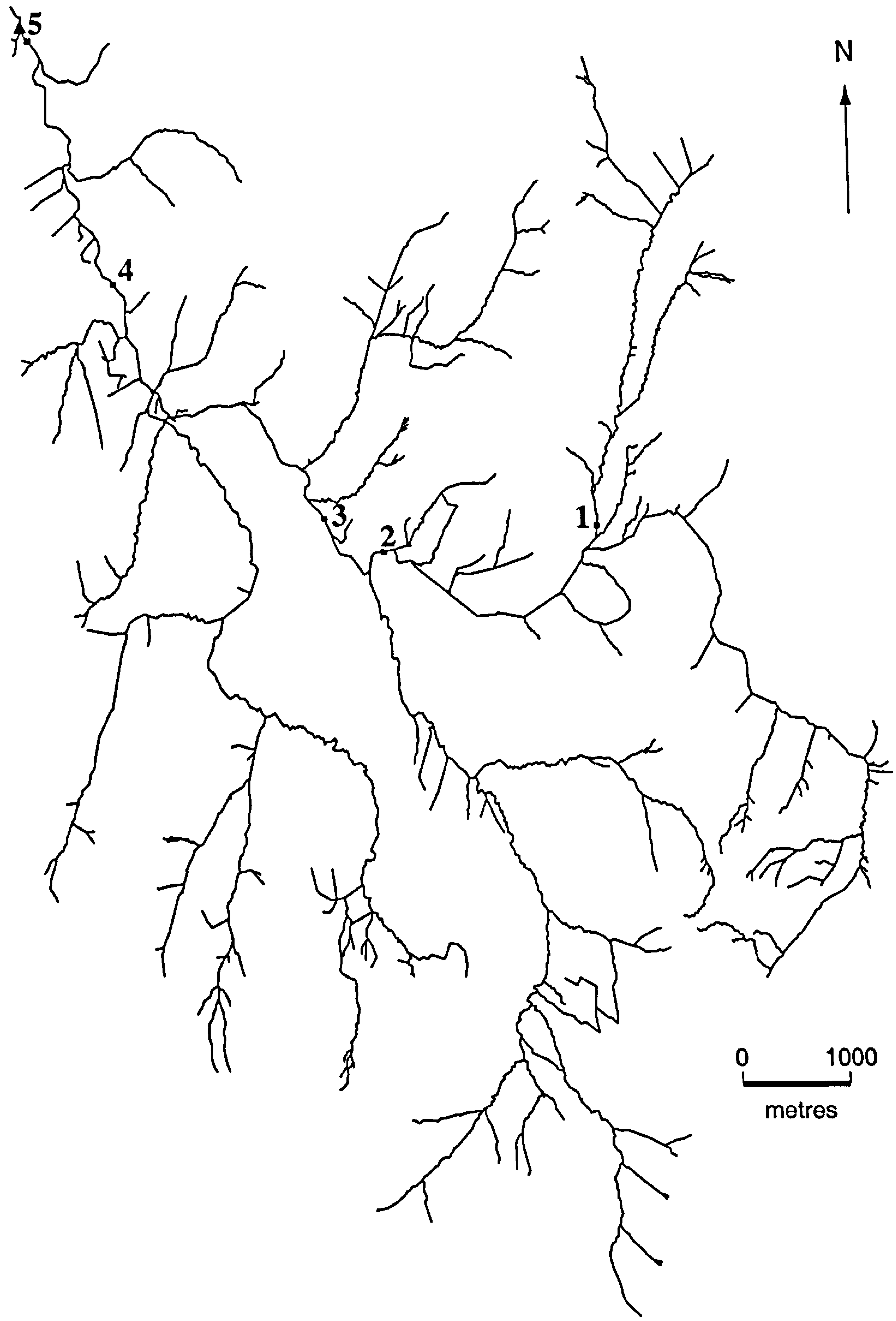
River	Site number	Site name	Grid reference	Total stream length upstream from the site to the source (km)	Distance downstream between sites (km)
Windrush	1	Naunton	SP 124 2305	27.84	0.00
	2	Aston farm	SP 145 215	32.03	4.19
	3	New Bridge	SP 179 176	39.27	7.24
	4	Fox Inn	SP 205 132	46.61	7.35
	5	Asthall	SP 291 115	59.34	12.73
	6	Minster Lovell	SP 319 111	64.41	5.07
	▲	Gauging station (Worsham)			

Figure 5.2a River Windrush showing study sites



River	Site number	Site name	Grid reference	Total stream length upstream from the site to the source (km)	Distance downstream between sites (km)
Seven	1	Rosedale	SE 680 014	0.41	0.00
	2	Bell end	SE 714 965	27.93	7.62
	3	Hartoft	SE 748 924	74.75	6.72
	4	Lower Askew	SE 745 899	77.65	2.90
	5	Normanby	SE 735 826	125.21	12.74
	▲	Gauging station (Normanby)			

Figure 5.2b River Seven showing study sites



River	Site number	Site name	Grid reference	Total stream length upstream from the site to the source (km)	Distance downstream between sites (km)
Livet	1	Suie	NJ 274 243	13.0	0.00
	2	Forest	NJ 247 241	41.94	2.94
	3	Footbridge	NJ 237 246	74.75	1.03
	4	Bridge	NJ 213 265	135.41	3.55
	5	Distillery	NJ 201 290	135.86	2.89
	▲	Gauging station (Minmore)			

Figure 5.2c River Livet showing study sites

drainage creating conditions that suit the development of peaty soils with bogs and blanket peat occurring frequently at higher levels. The till is sandy and unconsolidated and includes rock fragments that are fairly angular.

5.4 Choice of sites

The research focuses exclusively on downstream changes in the main river within each of the three catchments. It was not within the scope of the research to observe channel changes extending to the entire river network and the purpose of the study was to identify changing channel geometry and behaviour in response to changing catchment characteristics on the main river.

Five study sites were chosen on each river, the first site located as close to the source as possible and the final site on a natural reach close to the gauging station. The river network and site locations for each catchment are shown in figure 5.2a, b and c. The spacing between the remaining sites was estimated by dividing the distance between the first and last site into equal segments shown in figure 5.3.

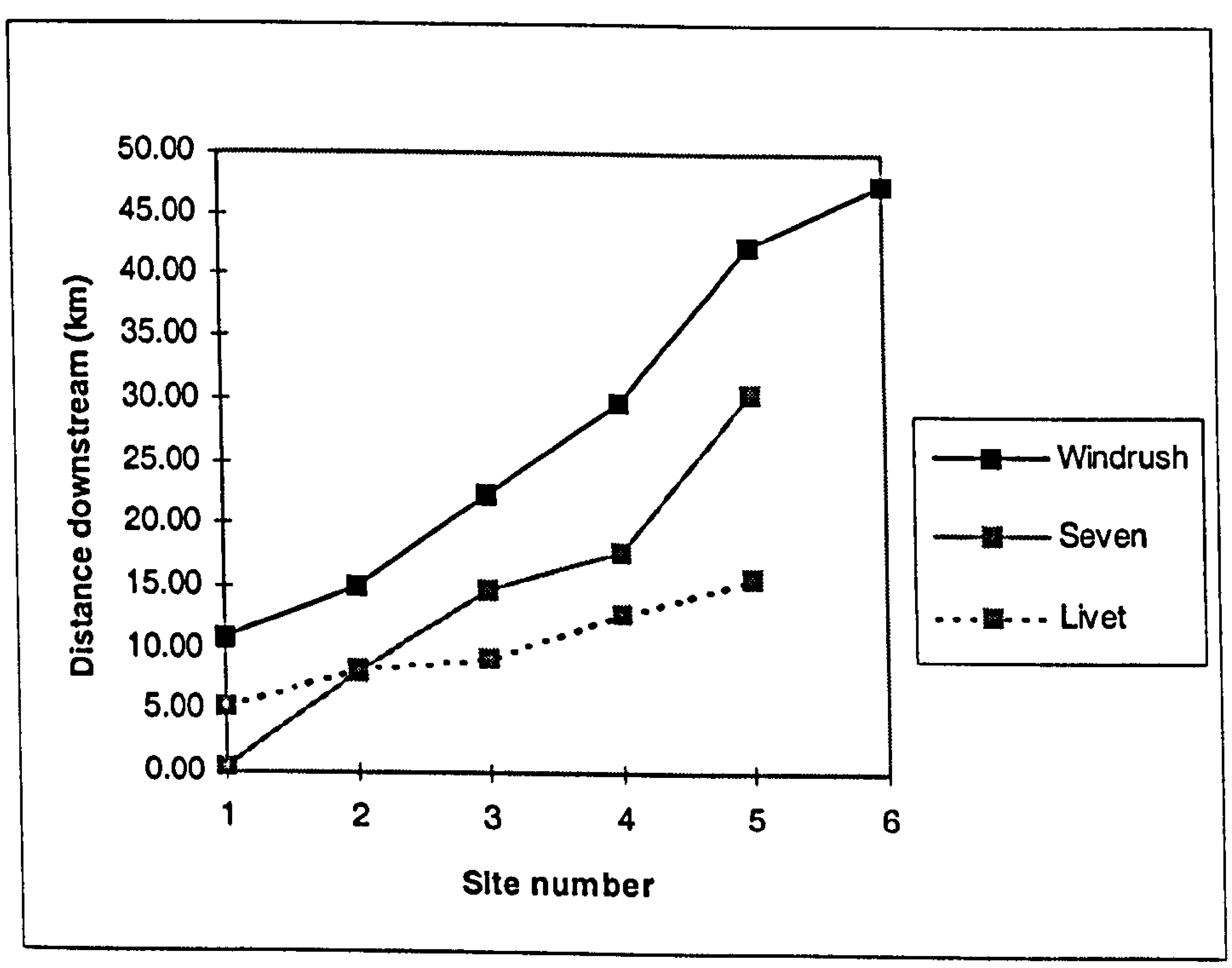


Figure 5.3 **Distance downstream of each site**

It was not always possible to locate the sites at exactly equal intervals downstream because other factors had an important influence on site selection. The first issue to consider was access, in terms of the site itself and surrounding upstream and downstream reaches. Land ownership and fishing rights prevented access at some sites. The condition and state of the reach also had an influence as it was important to select reaches that were in a semi-natural condition, with minimal upstream or downstream disruption and located on a straight section of channel. Each site was selected on the basis of access, condition and state observed during fieldwork but was guided by the estimated intervals calculated for each river.

5.5 Field work methodology

The fieldwork in each catchment took between one and two weeks during which time the river was observed in as many places as possible, often by walking the reaches between sites. At each site, the upstream and downstream sections were observed to gain a perspective of river channel behaviour and the field investigation took the same form as the national study where three cross-sections were surveyed according to the method outlined in section 4.4.3 and a general geomorphological survey was carried out for whole reach (section 5.5.1). In addition, detailed surveys were undertaken at each cross-section where information about bank size, material and stability, vegetation and substrate were recorded. Consequently, there were three section specific geomorphologcial assessments for each site. The purpose and structure of the geomorphological surveys are discussed in section 5.5.1.

5.5.1 Geomorphological surveys

The geomorphological survey was developed to address the objectives of the catchment study and was based on several currently available geomorphological and riverine surveys. It is important both in terms of the fieldwork constraints and the research outcomes, to link the survey structure specifically to the research aims. Each geomorphologcial survey is written with a different purpose in mind and it is crucial to include the necessary information but at the same time to omit sections of previous surveys which are irrelevant to the current research and which simply lead to data overload. The limitations of the survey used for the national study were also used to guide and improve the structure of the geomorphological surveys in the catchment study.

I GEOMORPHOLOGICAL SURVEY REACH SCALE

A Background desktop survey

River	
Site	
Grid reference	
Altitude	
Planform	
Slope	
Total Channel length	
Total trunk length	
No of tributaries	
Width of valley floor	
Geology	

B Landuse and valley description

Floodplain		Riparian buffer strips		Terraces		Vegetation	
None		None		None		None	
< 1 river width		Indefinite		Indefinite		Pasture	
1-5 river widths		Fragmentary		Fragmentary		Arable	
5-10 river widths		Continuous		Continuous		Shrubs	
> 10 river widths		Strip width		No. of terraces		Deciduous	
Alluvium		None		Trash lines		Coniferous	
levees		< 1 river width				Mixed	
		1-5 river widths					
		> 5 river widths					

Landuse in the valley

	LH	RH	Upstream
Vegetated			
Urbanised			
Partly built up			
Riparian buffer strip			
Road development			
Reservoir			
Other			

Predominant valley form

Shallow vee	
Deep vee	
Gorge	
Concave/bowl	
Terraced valley floor	
Symmetrical floodplain	
Asymmetrical floodplain	

Figure 5.4 **Part 1 Geomorphological survey reach scale**

C Channel Characteristics

Planform		Morphology		Description	1,2,3	Present	
Straight		Symmetrical		Straight deep			
Sinuous		Asymmetrical		Straight shallow			
Irregular meanders		Rosgen type		Chute			
Regular meanders		1		Pool			
Multi thread		2		Riffle			
		3		Run			
				Slack			

D Bed material description

Dominant		Bed forms		Bar types	
Clay		Flat bed		None	
Silt		Ripples		Pools and riffles	
Sand		Dunes		Alternate bars	
Gravel		Islands or bars		Point bars	
Cobbles				Mid-channel bars	
Boulders				Diagonal	
Bedrock				Junction bars	
				Sand waves	
				Dunes	

E Gradient

1-10m	
10-20m	
20-30m	
30-40m	
40-50m	

F Field Sketch

Figure 5.4 (cont'd) **Part 1 Geomorphological survey reach scale**

The geomorphological survey for the catchment study was split into two parts: Part I, the Reach Scale Survey to assess the characteristics of the whole reach and assess catchment conditions (figure 5.4); and Part II, Section-Specific Surveys, detailed geomorphological surveys undertaken at each of the three cross-sections to investigate in detail the stability of the reach and dominant controls (figure 5.7).

Part I: Geomorphological Survey Reach Scale

The Geomorphological Survey Reach Scale begins with a desktop study (Section A) based on 1:25000 scale maps of the catchments. The number of meanders over a 500m reach upstream and downstream of the site was used as a measure of the planform. Slope was calculated as the total drop in metres over one kilometre encompassing the survey reach. Total channel length (TCL) was obtained from digitised maps of the catchment (described in section 5.5.2) and refers to the total length of the river network upstream from the site. Distance Downstream (DD) refers to the length of the main river channel excluding tributaries. Width of the valley floor at the site was measured from 1:25000 scale maps.

Sections B to E of the geomorphological survey reach scale, were carried out in the field. Section B is a general assessment of the lateral and catchment controls on the channel form. The first part records information about the valley floor divided into the categories floodplain, buffer strip, terrace and vegetation based on Thorne (1993, Section 2, part 3). Landuse in the valley was recorded using the scheme proposed by Brookes (1996); this was also used in the national survey and found to be well adapted for the UK. The predominant valley form was classified according to categories used in the River Habitat Survey (1995) and is illustrated in figure 5.5.

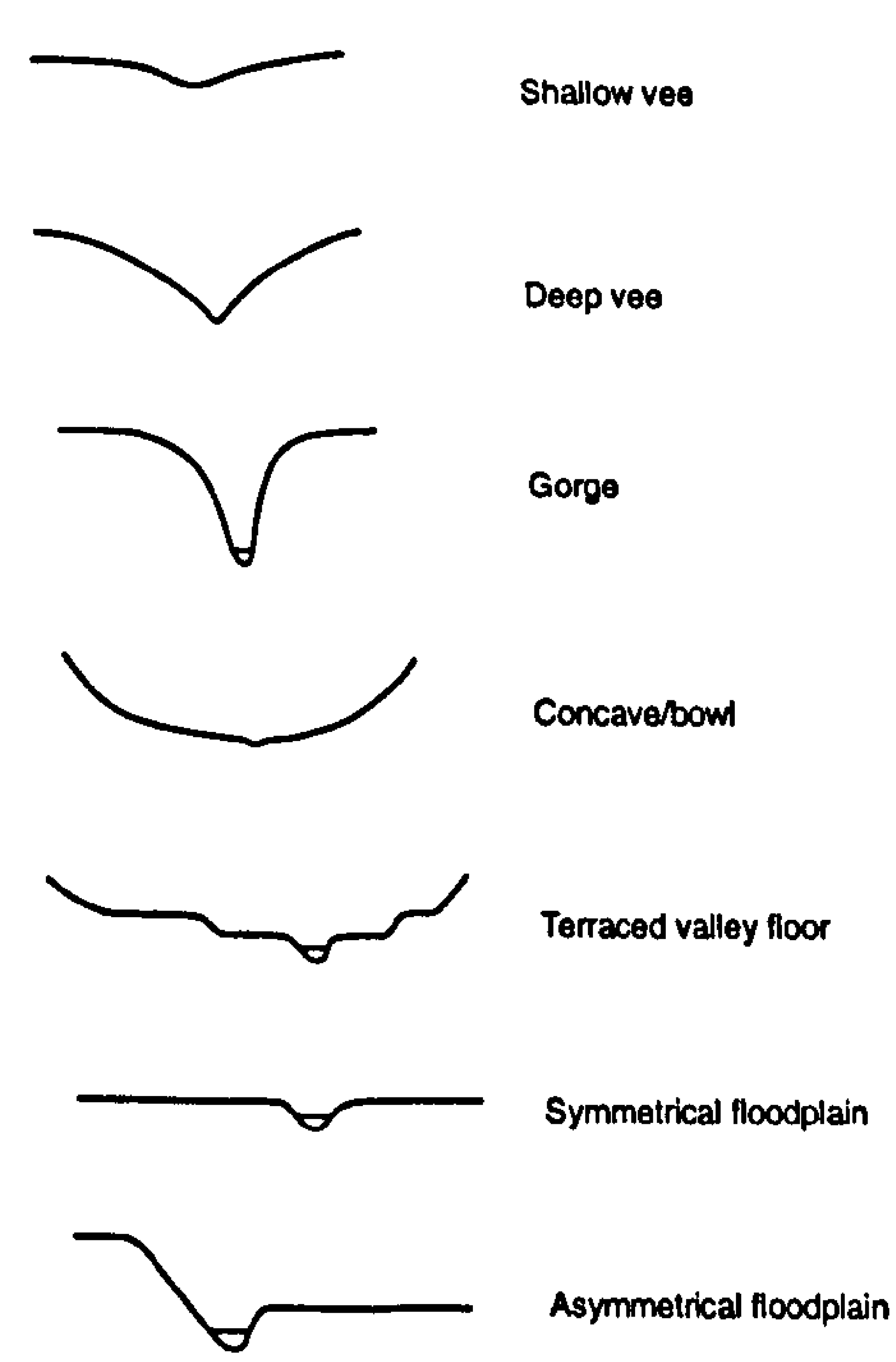


Figure 5.5 Predominant valley forms (from the River Habitat Survey, 1995)

Section C provides an overview of the channel characteristics along the whole reach in terms of the planform and morphology. The planform categories were based on Thorne (1993; Section 2, part 5, Guidelines, p.32). The morphology of the channel was described according to seven different terms defined specifically for this research in table 5.4.

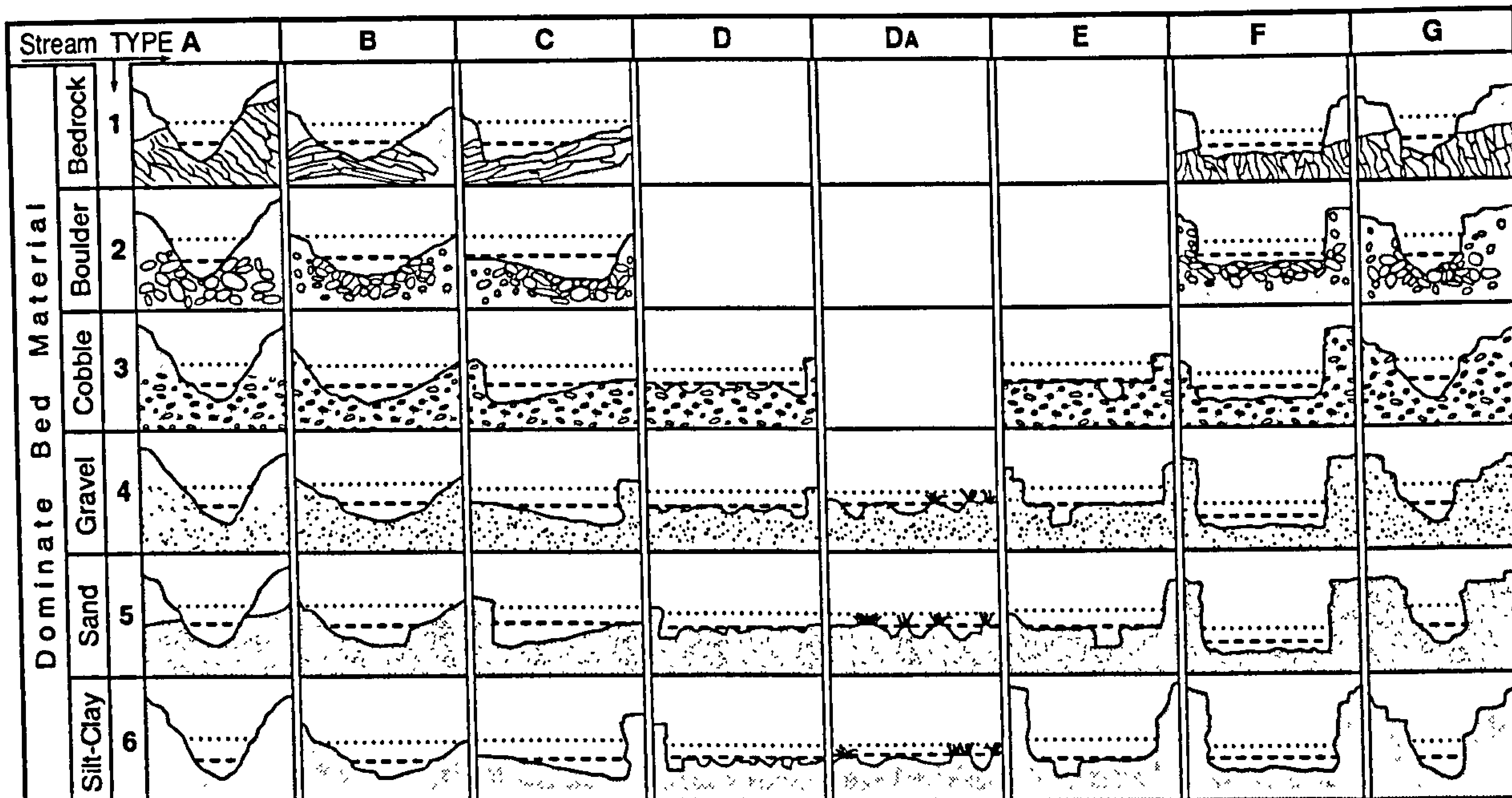
The classic dichotomous riffle-pool classification has dominated fluvial geomorphology for many decades but it is often not suitable to adequately define all river reaches. Riffle-pool sequences develop in gravel-bed rivers as a means of self adjustment. There is no conclusive theory on the development of pools and riffles and many of the ideas concerning their formation and thus what they can be used to indicate in terms of stability, remain speculative (Knighton, 1998, p.198). In many gravel bed rivers the riffle-pool sequence may not be in evidence and other morphological classifications can be used to describe the stage of channel development. The degree to which the riffle-pool sequence has developed varies with the bed material size relative to the flow conditions in a reach since the ability of a stream to modify its bed depends on the mobility of the available material and therefore the frequency with which competent flows occur. In some channels the riffle pool sequence may have been disrupted by an alteration to the flow regime or external influence on the channel, and could be an indicator of instability, although as mentioned above there is still confusion about the exact process of formation.

Alternating steps and pools are a feature of mountain streams flowing over slopes greater than 3-5% (Chin, 1989; Knighton, 1998, p. 201) and appear to be a fundamental element of steep fluvial systems. For other river channels, for example chalk or clay bed rivers, the riffle pool sequence does not occur and the terminology must be extended to cover various channel forms. Some of the terms in table 5.4 are frequently used in fluvial geomorphology (Knighton, 1998, Richards, 1982), but the terms *'deep straight'* and *'shallow straight'* were developed on the basis of fieldwork undertaken during the national study which showed that many channels did not have a developed pool riffle sequence.

Table 5.4 Channel morphology; terms and definitions

Term	*Definition*
Deep straight	A straight section of river which is relatively deep >0.5m with uniform geometry. Often alternating with shallow straights, preceding the development of riffle-pool sequence. Similar to an extended pool but faster flowing and not associated with an asymmetrical profile.
Shallow straight	A shallower section, but not yet attaining the characteristics of a riffle. Remains fast flowing, but has an unbroken surface even at low flow.
Pool	Deep section dominated by circular currents, often developed close to or at meander bends.
Riffle	Fast flowing shallow section with broken surface.
Run	Different to a riffle as the surface is broken by boulders in several places causing split flow, some of which can remain deep in the channels.
Chute	Section before a pool where water is channelled; fast flowing over a flat bed. Often bedrock controlled.
Slack	Ponded backwater with no flow.

The Rosgen (1994) classification of natural channels (figure 5.6) was also used to investigate whether this classification is suitable for differing river types in the UK and as a basis for comparison of channel types between the catchments. However, the use of the classification was found to be limited and difficult to apply to UK channels and was consequently not used during the analysis of results. The characteristics of the river bed were recorded in section D, including the dominant bed material, bed forms and bar types (Thorne, 1993, Section 2, part 7). Section E was used to record the gradient of the river bed and an average gradient over a 50 metre reach was calculated for each channel.



	A	B	C	D	DA	E	F	G
Entrchmnt	< 1.4	<1.4 – 2.2	> 2.2	n/a	> 4.0	> 2.2	< 1.4	< 1.4
W:D ratio	< 12	> 12	> 12	>40	< 40	< 12	> 12	< 12
Sinuosity	1 – 12	>1.2	> 1.4	n/a	variable	< 1.5	> 1.4	>1.2
H_2O Slope	.04 – .099	.02 – .039	< .02	< .04	< .005	< .02	< .02	.02 – .039

Figure 5.6 Classification of stream types after Rosgen (1994)

Part II : Geomorphological Survey - section specific surveys

The section specific surveys (shown in figure 5.7) were carried out at each of the three cross-sections with the purpose of gaining detailed information about the stability of each reach and the local factors controlling channel geometry.

i)Bank material and stability

There has been a large amount of work on bank stability (section 2.6.1) but much of it has been applied to problems of bank erosion and not integrated into work on sensitivity and channel geometry changes downstream. The stability of the banks was evaluated according to physical parameters such as bank height, profile and gradient and bank material type and strength. Many different methods have been used to measure bank shear strength and resistance to erosion (Grissinger, 1982). Samples were taken from both banks at each section and particle size analysis was undertaken to obtain percentage silt clay in the banks (M). To measure shear strength *in situ*, the only option possible within the research constraints was the use of a shear vane. Ten shear vane tests were carried out vertically on the top of the river bank and ten into the face of the bank normal to the bank surface.

II SECTION SPECIFIC SURVEY

LH BANK AND RH BANK

Bank materials		Details		Bank type	y	n	Shear vane	Top	Face
Silt/clay		Bankfull height (m)		Cohesive			1		
Sand/silt/clay		Graduated		Non cohesive			2		
Sand/silt		Angle		Composite			3		
Sand/silt		Profile type		Layered			4		
Sand/gravel		Profile		Even layers			5		
Gravel				Thick/thin			6		
Gravel/cobbles				**Depth of samples**			7		
Cobbles				1			8		
Cobbles/boulders				2			9		
Bedrock				3			10		

Bank stability		Tension cracks		Sediment accumulation at toe	
Undercutting		None		None	
Depth (m)		Occasional		Individual grains	
Height (m)		Frequent		Aggregates and crumbs	
Roots exposed		Crack depth		Root based clumps	
Bare earth		Slumped blocks		Small soil blocks	
Signs of abrasion				Medium soil blocks	
				Large soil blocks	
				Cobbles and boulders	
				Boulders	

Bank vegetation - top of bank

Vegetation		Trees		Density and spacing along bank		5m
None/fallow		None		None		
Cultivated		Deciduous		Sparse/clumps		
Grass and flora		Coniferous		Dense/clumps		
Reeds and Sedges		Mixed		Sparse/continuous		
Shrubs		**Tree lining**		Dense/continuous		
Saplings		Continuous				
Trees		Broken				
Age (0,1,2,3)		In parts				
Diversity (0,1,2,3)		Single				

Face of bank

Vegetation		Roots		Density and spacing
None/Bare earth		Normal		None
Grass and flora		Exposed		Sparse/clumps
Reeds and Sedges		Adventitious		Dense/clumps
Shrubs		Depth of exposure		Sparse/continuous
Saplings		Average width of roots		Dense/continuous
Trees		Density in $0.5m^2$ (%)		
Trees overhanging				
Aquatics				

Figure 5.7 Part II : Geomorphological Suvery Reach Specific

AT EACH SECTION

Channel Characteristics

Bed		**%**	**Size** a	b	c	**Morphology**		**General synopsis**	
Clay		1				Deep straight		Stable	
Silt		2				Shallow straight		Unreliable	
Sand		3				Chute		Unstable dormant	
Gravel		4				Pool		Unstable active	
Cobbles		5				Riffle		Eroding dormant/active	
Boulders		6				Run		Advancing dormant/active	
Bedrock		7				Slack			
		8							
		9							
		10							

Figure 5.7 **(Cont'd) Part II : Geomorphological Suvery Reach Specific**

This permitted an investigation of the strength of the bank material in different directions, whether there was a wetting effect and the influence of roots on bank strength. The bank profiles were sketched and then classified according to the profile types depicted in Gordon *et al.,* (1992). Erosional features were recorded and used to identify bank instability. The extent of bank undercutting was measured and signs of abrasion and root exposure noted. Bank failure was recorded and any signs of instability noted from tension cracks in the banks.

ii) Vegetation

The effects of riparian vegetation in terms of bank stability are complicated and vegetation cannot simply be classed as a benefit or a liability without consideration of its type, age and density (Thorne and Osman, 1988) (see discussion in Chapter 2, section 2.6.3). The vegetation was surveyed for both the bank top and the face of the bank based on Thorne (1993, section 4, part 9). The vegetation was noted and then coded according to age and diversity as shown in table 5.5. The density of the vegetation was also recorded along the banks and 5m back from the channel. Spacing of vegetation describes the distribution on the bank surface. Particularly, it refers to whether there are clumps of vegetation leaving areas of the bank vulnerable to erosion, whether there are closely spaced clumps of plants or whether there is a continuous cover of plants. In this context the term 'uniform' refers to the degree of spacing between dense and sparse.

Table 5.5 Vegetation types

Class	*Age*	*Diversity*
0	No vegetation	No vegetation
1	Young	Uniform
2	Mature	Simple (2 or more species)
3	Old	Complex (>4 species)

iii) Substrate and bed material transport

The percentage of different bed material types were visually analysed at each section (Gordon *et al.* 1992). The transporting capacity of the stream was measured by selecting ten of the largest stones and measuring the a, b and c axes. The average for each site was calculated for each axis and taken as percentage of the bankfull width (K.J. Gregory (1997) personal communication).

5.5.2 Discharge information

Mean annual flood values were calculated from the flow records obtained from the gauging stations in each catchment, shown in figure 5.2 a, b, and c. The lack of gauging station networks in the catchments (discussed in section 5.2), meant that it was impossible to derive channel geometry - discharge relationships for each site downstream through the catchment and as a result a morphometric approach was adopted.

Total Channel Length (TCL) was selected as the morphometric measure in the catchment study because of the difficulties associated with calculating catchment area for closely spaced downstream sites (Brookes, 1987a) and secondly the availability of large scale (1:25000) maps in the UK (Gregory and Walling, 1973) from which stream length can be accurately derived. TCL was calculated using the blue line method (Horton, 1945) in which the length of the river network is measured from the blue lines on topographic maps. This was done by digitising the river networks, using ARCINFO. Gan *et al.* (1992) discussed the problems surrounding the measurement of stream length and stated that the length of an intricately sinuous line tends to increase the more accurately it is measured, highlighting the importance of consistency in the scale of map used and the method of measurement. To ensure the accuracy of digitised data, a consistent technique was developed for dividing the streams into segments. Straight reaches were divided according to breaks in the planform and meanders were measured to the apex of the meander bend.

Other limitations of TCL must also be considered when carrying out morphometric analysis. The total length of the river channel network only takes into account surface water drainage thus any water entering the channel from groundwater reserves is not represented. This may be of most concern in the Windrush catchment where Oolitic limestone springs contribute heavily to discharge values and also in the Seven where there is some seepage from neighbouring Farndale, in the catchment of the River Dove. The blue line method only represents a static channel network and does not take into account changes in channel planform which are an integral part of channel form adjustment. Finally, it must be emphasised that TCL is not a replacement for discharge, but an alternative measure that cannot incorporate the hydrolgical characteristics which vary from catchment to catchment. However, as discussed in Chapter 2 (section 2.5) channel morphometry is an extremely useful method where flow records are not available and can be used to assess the downstream changes in river morphology which are so important to understanding the behaviour of the reach within the context of the catchment. The method is suited to the humid temperate climate where stream networks are perennial and channel morphometry has been used successfully in the UK to document downstream changes (Gregory and Park, 1974; Park, 1977; Petts, 1979; Brookes 1987a).

5.6 RESULTS FROM THE CATCHMENT STUDY

The aim of the catchment study was to interpret changes in channel geometry at the reach scale in the context of downstream changes at the catchment scale. The analysis therefore focuses on how channel geometry changes downstream in each catchment and the influence of local and catchment controls on river channel from and adjustment. Before discussion of the results commences, a series of photographs from each site downstream are presented first to give an each of the catchments an environmental context and illustrate the downstream changes.

Photo 5.3 River Windrush at Naunton (W1)

Photo 5.4 River Windrush at Aston Farm (W2)

Photo 5.5 River Windrush at New Bridge (W3)

Photo 5.6 River Windrush at Fox Inn (W4)

Photo 5.7 River Windrush at Asthall (W5)

Photo 5.8 River Windrush at Minster Lovell (W6)

Photo 5.9 River Seven at Rosedale Head (S1)

Photo 5.10 River Seven at Bellend Farm (S2)

Photo 5.11 River Seven at Hartoft (S3)

Photo 5.12 River Seven at Lower Askew (S4)

Photo 5.13 River Seven at Normanby (S5)

Photo 5.14 River Livet at Suie (L1)

Photo 5.15 **River Livet at Forest (L2)**

Photo 5.16 **River Livet at Footbridge (L3)**

Photo 5.17 **River Livet at Bridge (L4)**

Photo 5.18 **River Livet at Distillery (L5)**

The analysis is structured according to the three main aims outlined in section 5.1. The results from the cross-sectional surveys at each site are presented in section 5.6.1. The changes in channel geometry downstream are then discussed terms of the relationship between bankfull width and Total Channel Length (5.6.2) and factors operating to control channel form at the catchment (5.6.3) and local scales (5.6.4). Finally the stability of the river channels downstream will be addressed (5.6.5) on the basis of the results from the geomorphological surveys carried out at each site. The final section (5.7) summarises the main findings from the catchment study.

5.6.1 Changes in channel geometry downstream

Channel geometry was measured at three cross-sections at each site from which average values for channel dimensions were derived (shown in table 5.6). Channel dimensions, bankfull width (w), mean depth (dm), maximum depth (dmax) and channel capacity (Ab), were plotted for each site downstream on the Windrush (fig 5.8a), Seven (5.8b) and Livet (5.8c).

Table 5.6 **Geometric and Morphometric data for each of the sites in the three study catchments**

Site	ID	w (m)	d (m)	dmax (m)	A_b (m^2)	R	W:D	Gradient (m m-1)	TCL (km)
Windrush									
Naunton	W1	2.63	0.47	0.54	1.20	1.02	5.64	0.0035	27.90
Aston	W2	8.94	0.44	0.66	4.18	0.40	20.46	0.0045	34.93
New Bridge	W3	9.86	0.62	0.85	5.96	0.55	15.88	0.0038	78.99
Fox Inn	W4	8.33	0.94	1.16	8.17	0.77	8.89	0.0031	107.52
Asthall	W5	14.62	0.91	1.34	13.63	0.81	16.12	0.0042	149.92
Minster	W6	13.31	1.06	1.33	14.38	0.92	12.51		156.98
Seven									
Rosedale	S1	2.91	0.87	1.56	2.27	0.54	1.87	0.026	0.41
Bellend	S2	6.88	1.07	1.52	7.27	0.82	4.52	0.0073	27.93
Hartoft	S3	12.89	1.05	1.57	14.22	0.90	8.23	0.007	74.75
Askew	S4	11.28	1.26	1.80	14.84	1.03	6.27	0.0052	77.65
Norman	S5	12.62	1.13	1.63	12.11	1.24	5.60		125.21
Livet									
Suie	L1	4.56	0.51	0.68	2.29	0.41	6.96	0.0087	13.00
Forest	L2	8.43	0.41	0.62	3.78	0.37	13.74	0.0017	41.94
Footbridge	L3	8.30	0.96	1.33	8.32	0.78	6.26	0.0073	74.75
Bridge	L4	15.66	1.40	1.99	22.91	1.19	7.86	0.0052	135.41
Distillery	L5	15.13	1.24	1.61	19.00	1.06	9.42	0.0024	135.86

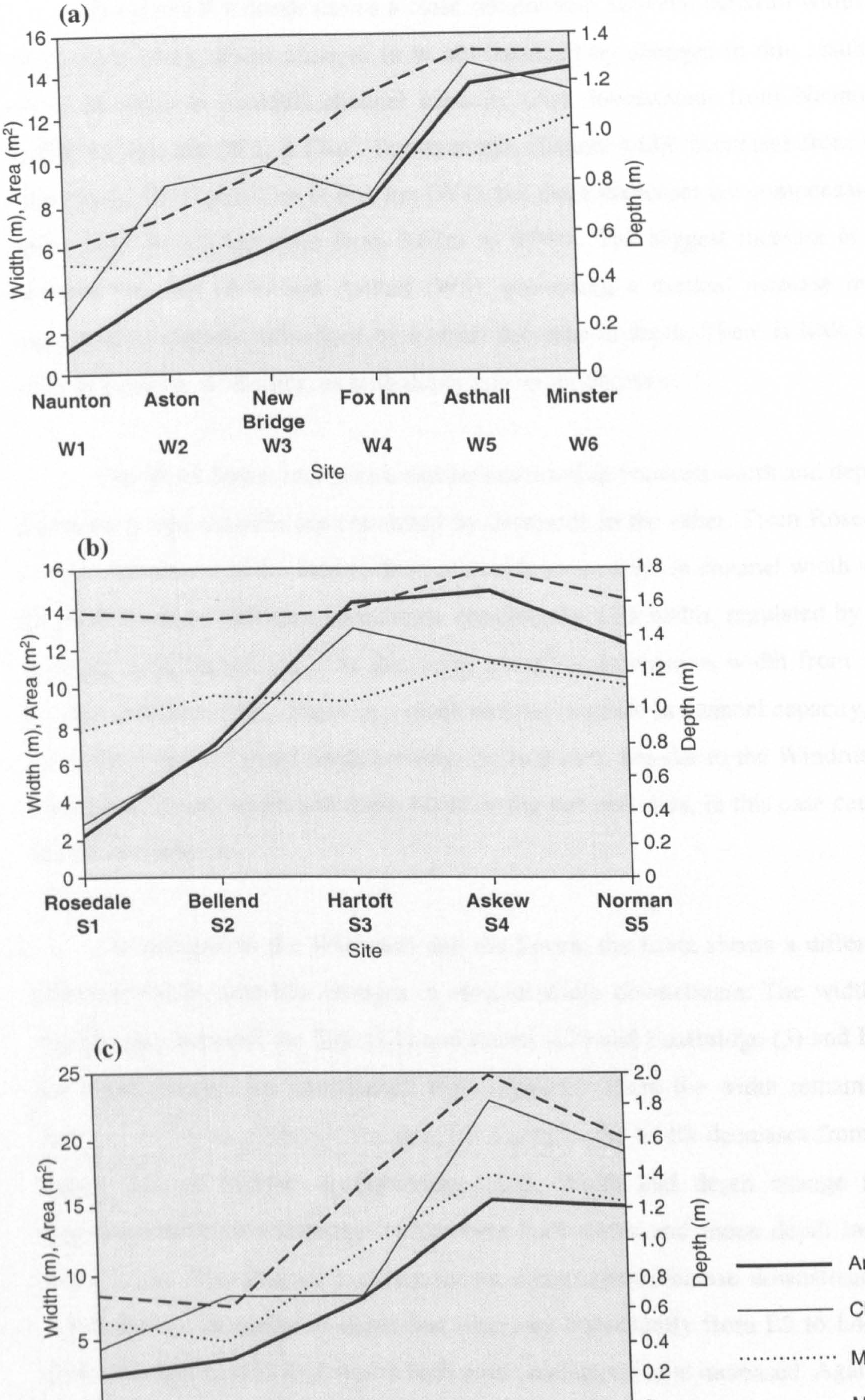


Figure 5.8 **Downstream changes in channel geometry on (a) the River Windrush, (b) the River Seven and (c) the River Livet. All measurements are at bankfull level.**

The River Windrush shows a close relationship between bankfull width (w) and mean depth (dm), where changes in w are balanced by changes in dm, resulting in a steady increase in bankfull channel capacity (A_b) downstream from Naunton (W1) 1.20m^2 to Fox Inn (W2) 8.17m^2. For example, channel width decreases from 9.86m at New Bridge (W3) to 8.33m at Fox Inn (W4), but these decreases are compensated for by mean depth which increases from 0.62m to 0.94m. The biggest increase in width is between Fox Inn (W4) and Asthall (W5), prompting a marked increase in channel capacity only slightly influenced by a small decrease in depth. There is little change in channel capacity at Minster, as both depth and width decrease.

The River Seven indicates a similar relationship between width and depth, where increases in one variable are countered by decreases in the other. From Rosedale (S1), close to the source of the Seven, there is a uniform increase in channel width and depth. Channel capacity continues to increase consistently with width, regulated by decreases in depth until Hartoft (S3). At this point a sudden decrease in width from 12.89m to 11.28m at Askew (S4), results in a much smaller increase in channel capacity, sustained by an increase in channel depth between the two sites. Similar to the Windrush, there is a decrease in both width and depth between the last two sites, in this case causing a fall in channel capacity.

In contrast to the Windrush and the Seven, the Livet shows a different pattern characterised by step-like changes in channel width downstream. The width increases significantly between the Suie (L1) and Forest (L2) and Footbridge (3) and Bridge (L4) but these changes are interspersed with segments where the width remains relatively constant and even slightly decreases, for example, the width decreases from 8.425m at Forest (L2) to 8.295m at Footbridge (L3). Width and depth change in opposite directions until the footbridge (L3) where both width and mean depth increase until Bridge (L4). The channel capacity shows a consistent increase downstream, which is dependent on increases in depth that increases consistently from L2 to L4, but shows greatest increase at Bridge where both width and depth have increased. Again, similar to the Windrush and the Seven, there is a decrease in both width and depth at the final site.

The maximum depth parameter was useful for comparison with mean depth, the difference between the two indicating the degree of variability in channel depth at each site. In the Livet (figure 5.8c), changes in maximum depth parallel changes in mean depth, indicating that there has been an overall change in depth at a site. This supports the finding that increases in channel capacity downstream in the River Livet are dependent on changes in channel depth. Maximum depth changes in the Windrush are much smoother and are not so closely associated with mean depth. For example, maximum depth increases at Aston (W2) and Asthall (W5) while mean depth decreases indicating greater variability in channel depth over the reach at these sites, perhaps resulting from localised scouring. It is interesting to note that the width at both these sites has also shown a marked increase, which could be significant in terms of channel stability. In the River Seven, the maximum depth stays constant whilst the mean depth varies downstream, indicating a constant maximum incision downstream whilst mean depth indicates variability. This supports the suggestion based on the relationship between channel width and capacity, that the River Seven is characterised by width adjustments as opposed to depth.

Changes in channel dimensions are dependent on the relationship between between width and depth, which influence channel shape. Changes in channel dimensions and shape are dependent on changes in channel gradient. Figures 5.9a, b, and c show changes in channel shape and gradient downstream in each river. The wetted perimeter is clearly dependent on channel width and the changes therefore reflect downstream changes in width described for all three catchments. The width:depth ratio (W:D) was used as a measure of channel shape where higher ratios indicate wide, shallow channels and lower ratios represent narrower deeper channels. In the River Seven (Figure 5.9b), the width:depth ratio is consistent with changes in width, highest at Hartoft (S3) before decreasing again until the final site at Normanby (S5). Gradient decreases downstream and does not appear to be associated with changes in channel shape. These findings agree with depth changes downstream which further support the finding that maximum incision remains constant downstream, implying that changes in depth are less influential than changes in width. The W:D ratio in the River Windrush, appears to be influenced more by changes in channel depth, as opposed to width as seen in the River Seven. The W:D increases at Aston (W2), indicating a wide shallow channel, where depth has decreased downstream and width has increased.

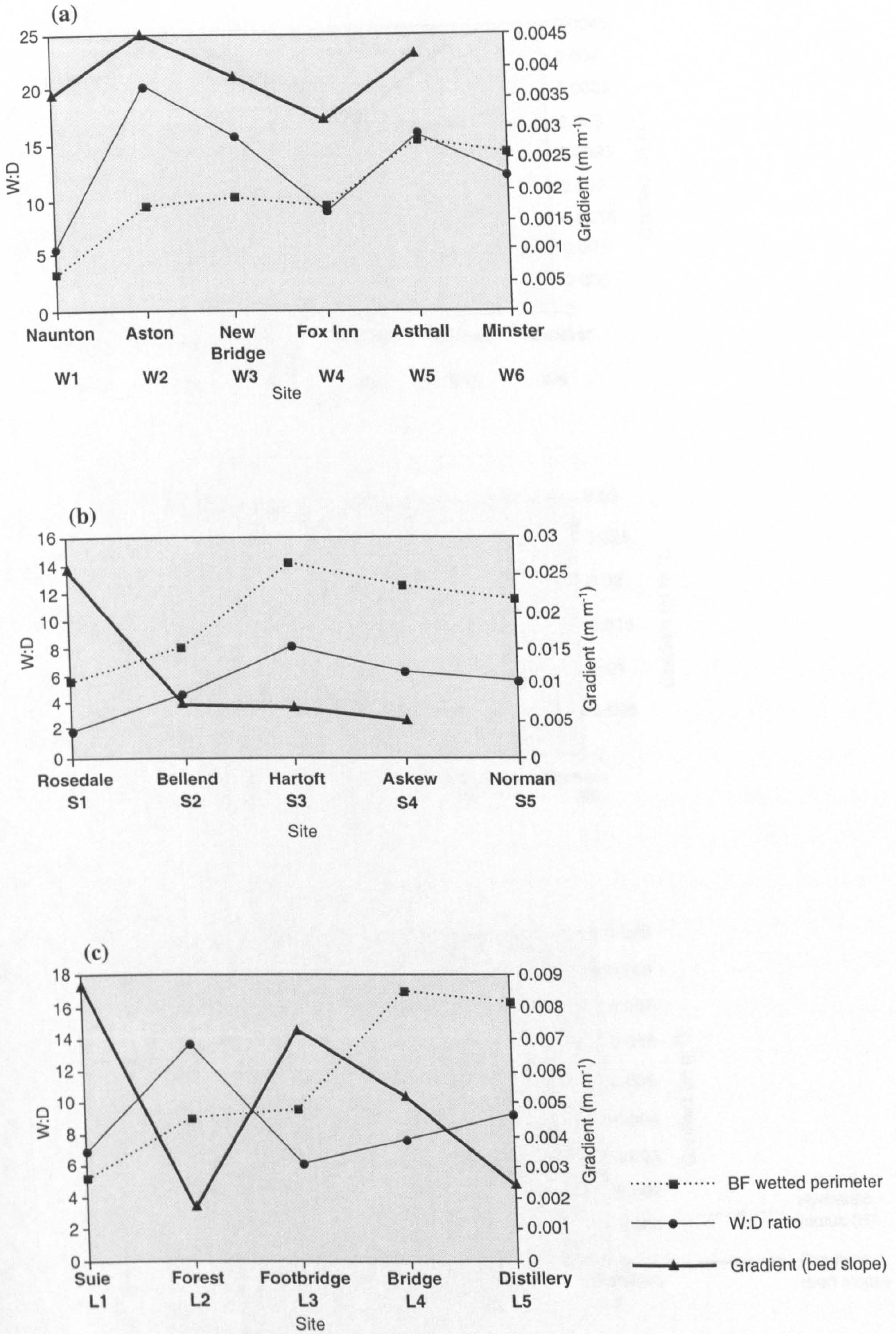


Figure 5.9 **Downstream changes in channel shape and gradient in (a) the River Windrush, (b) the River Seven and (c) the River Livet**

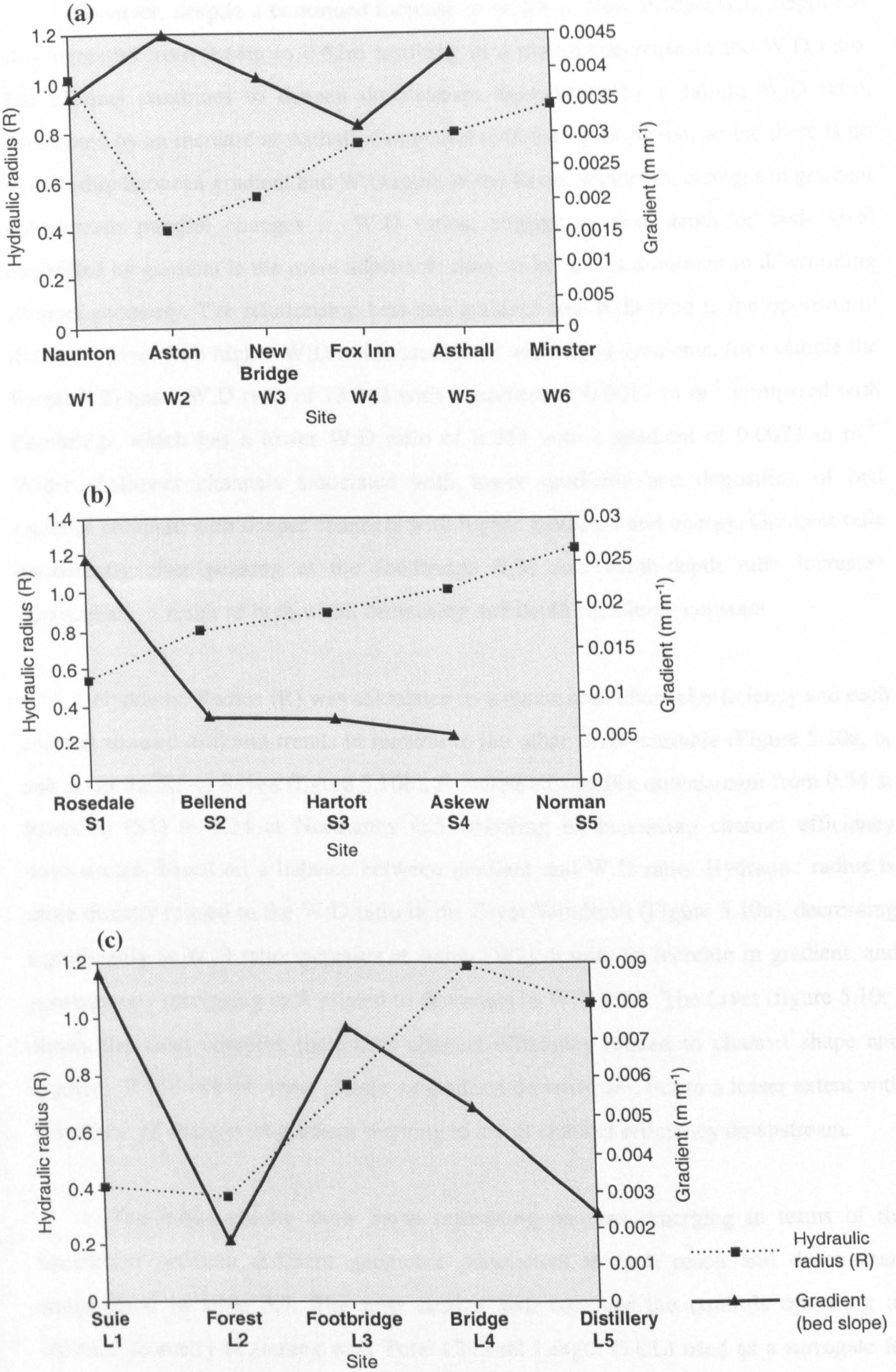


Figure 5.10 **Downstream changes in hydraulic radius and gradient in (a) the River Windrush (b) the River Seven and (c) the River Livet.**

However, despite a continued increase in width at New Bridge(W3), depth has also increased from 0.44m to 0.62m resulting in a marked decrease in the W:D ratio. The channel continues to deepen downstream represented by a falling W:D ratio, interrupted by an increase at Asthall. Compared with the River Seven, where there is no relationship between gradient and W:D ratio, in the River Windrush, changes in gradient downstream parallel changes in W:D ratios, suggesting that depth or bed- level controlled by gradient is the more adjustable than width and is dominant in determining channel geometry. The relationship between gradient and W:D ratio is the opposite in the River Livet with higher W:D ratios associated with lower gradients, for example the Forest (L2) has a W:D ratio of 13.742 with a gradient of 0.0017 m m^{-1} compared with Footbridge which has a lower W:D ratio of 6.255 with a gradient of 0.0073 m m^{-1}. Wider shallower channels associated with lower gradients and deposition of bed material compare with deeper channels with higher gradients and energy. Gradient falls consistently after peaking at the footbridge (L3) and width-depth ratio increases downstream, a result of both width decreasing and depth remaining constant.

Hydraulic Radius (R) was calculated as a measure of channel efficiency and each channel showed different trends in relation to the other shape variable (Figure 5.10a, b, and c). In the River Seven (figure 5.10b), R increased steadily downstream from 0.54 at Rosedale (S1) to 1.24 at Normanby (S5) showing an increasing channel efficiency downstream, based on a balance between gradient and W:D ratio. Hydraulic radius is more directly related to the W:D ratio in the River Windrush (Figure 5.10a), decreasing significantly as W:D ratio increases at Aston (W2) despite an increase in gradient, and subsequently increasing in R related to decreases in W:D ratio. The Livet (figure 5.10c) shows the most complex pattern of channel efficiency related to channel shape and gradient. R follows the same pattern as gradient downstream, but to a lesser extent with the effects of changes in gradient seeming to affect channel efficiency downstream.

The initial results show some interesting patterns emerging in terms of the interaction between different geometric parameters at each reach and downstream summarised in table 5.7. The next section will consider the controls operating on channel geometry beginning with Total Channel Length (TCL) used as a surrogate for discharge.

Table 5.7 **Summary of the downstream changes in channel geometry, gradient and form related to hydraulic radius**

River	Dimensions (w, d and dmax)	Gradient	Hydraulic radius (R)
Windrush	• A close relationship exists between w and d downstream where changes in w are balanced by changes in d, reflecting a steady increase in channel changes in A_b. • Changes between d and dmax were not always consistent indicating that bed-level changes are variable downstream. • Sites where dmax increases but dmean decreases coincide with the largest width increases suggesting localised scouring.	• Changes in W:D ratio are closely related to changes in local channel gradient. Increases in W:D in paralleled by increases in gradient suggesting that channel adjustment is controlled by bed-level changes.	• R is influenced by changes in W:D ratio. Channel efficiency decreases where W:D ratio increases, despite increases in gradient.
Seven	• A close relationship exists between w and d where changes in w are balanced by changes in d. • A_b increases steadily with width downstream. • dmax remains constant downstream indicating that incision is at a maximum and depth adjustments are therefore limited	• Gradient decreases consistently downstream. • Changes in W:D ratio closely reflect changes in width downstream and are not related to changes in gradient, suggesting that channel adjustment is width controlled.	• Channel efficiency increases steadily downstream as a result of changes W:D ratio related to gradient.
Livet	• Changes in w between sites are step-like where large changes in width are followed by little or no change. • Changes in d and dmax are closely related indicating consistent depth changes downstream.	• Increases in channel gradient are associated with decreases in channel gradient downstream indicating a mutual adjustment of channel shape and gradient. High W:D ratios are associated with lower gradients, but there is no consistent pattern downstream.	• Channel efficiency increases downstream but there does not appear to be a dominant influence of either gradient or W:D ratio.

5.6.2 The relationship between channel geometry and Total Channel Length.

The relationship between channel geometry and TCL, was initially investigated using regression analysis of data from all three catchments, with TCL as the independent variable and geometric parameters as the dependent. This was to establish the strength of relationships between channel geometry and discharge across three contrasting catchments and to identify whether regression relationships could be applied at a reach scale before examining downstream trends. Although the total number of observations was 16, these were average values representing data from 48 cross-sections, thus providing a sample that could be described as statistically large and appropriate for regression analysis. The residuals from each regression analysis were tested and found to be normally distributed. The summary statistics for each relationship are shown in table 5.8.

Table 5.8 Results from regression analyses between Total Channel Length and Channel Geometry.

	Observations	*Correl coeff*	*R2*	*SE*	*Intercept*	*Coeff*
Width	16	0.88	0.61	0.15	-0.26	0.26
Width (excluding W1)	15	-	0.87	0.08	-0.18	0.25
Dmean	16	0.62	0.12	0.3	0.052	0.18
Dmean (excluding SI and L1)	14	-	0.37	0.25	-2.74	0.75
Dmax	16	0.49	0.003	0.46	0.16	0.5
Channel Capacity	16	0.82	0.49	0.27	-0.84	0.27
Hydraulic radius	16	0.62	0.27	0.24	-0.19	0.24

The relationship between width and total channel length was the strongest, shown in figure 5.11. When all the sites were included in the analysis (line a, figure 5.11), the relationship has an R^2 value of 0.61. It is clear from the line fit plot, however, that one of the points is an outlier. The point corresponds to Naunton, site 1 on the River Windrush where the observed width is much greater than the predicted width for the TCL. This can be explained by the fact that the river is groundwater fed in the upper reaches and the Total Channel Length does not represent the discharge which is much higher than surface drainage patterns would suggest, accounting for the wider channel. When this site was excluded from analysis (line b, figure 5.11) the coefficient of determination increased from 0.61 to 0.87, showing that despite the differences in catchment conditions the relationship between TCL and bankfull width is strong. This reflects the findings from the national study.

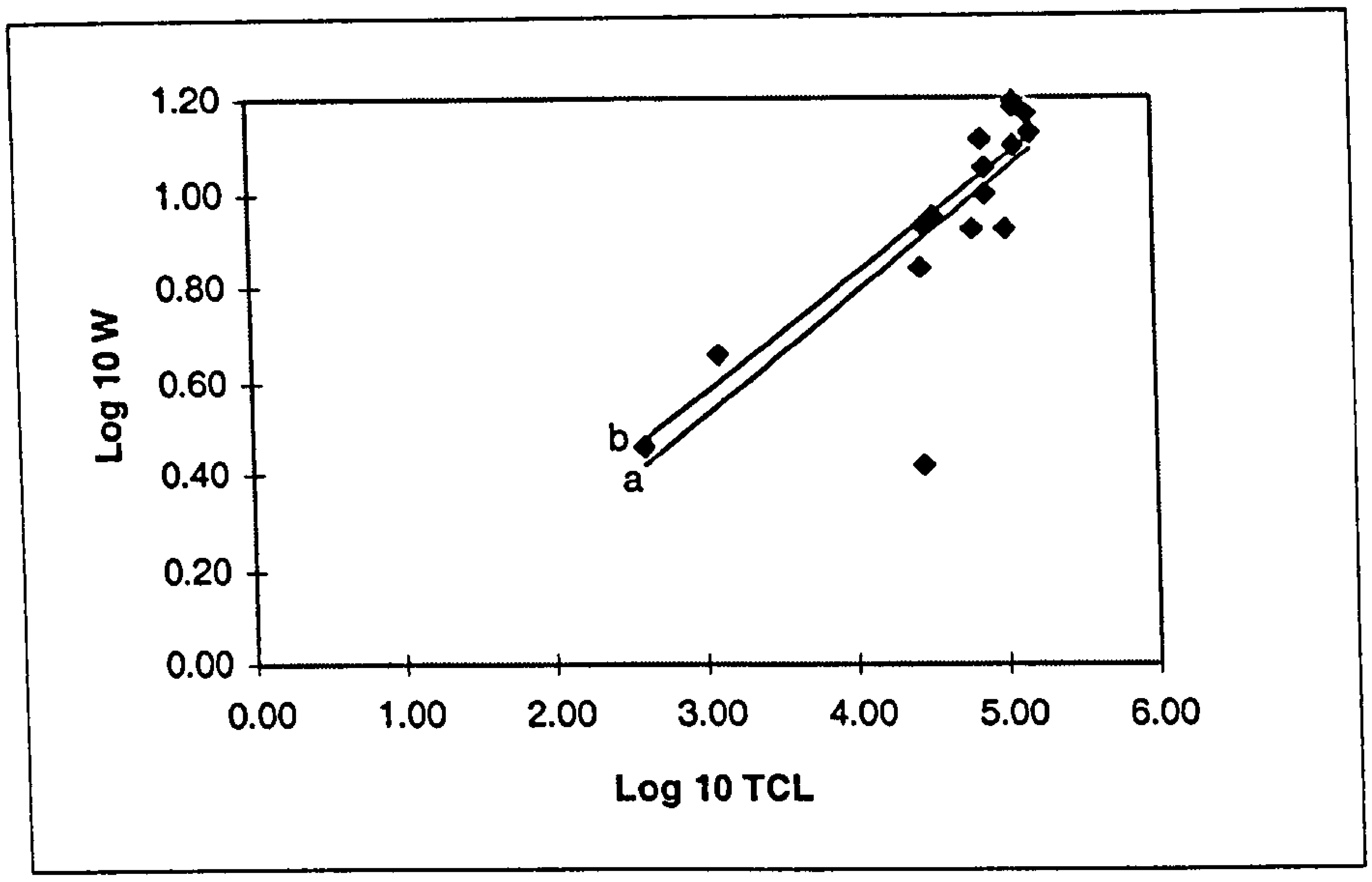


Figure 5.11 **The relationship between Total Channel Length (TCL) and bankfull width. a: y= 0.26 $x^{-0.16}$ for all sites, b: y = 0.25 $x^{-0.26}$ excluding Naunton (W1).**

In comparison, there was no relationship between mean and maximum channel depths and Total Channel Length, although a weak association (R^2 = 0.37) existed between mean depth and TCL, significant at 95% confidence levels, when the sites closest to the source on the Livet and Seven (marked by x in figure 5.12) are excluded.

Sites L1 and S1 are both over-deep in relation to TCL, perhaps as a result of their location. Both sites are in high energy environments, over 350 m, with responsive flow regimes resulting in maximum incision. The association between mean depth and TCL even excluding these sites is not strong (R^2 = 0.37) and shows that the downstream changes in channel depth are dependent on many factors other than discharge. Channel capacity (Ab) shows a relatively strong relationship with TCL (R^2 = 0.49) influenced by width and depth but again illustrates that other factors also affect channel capacity.

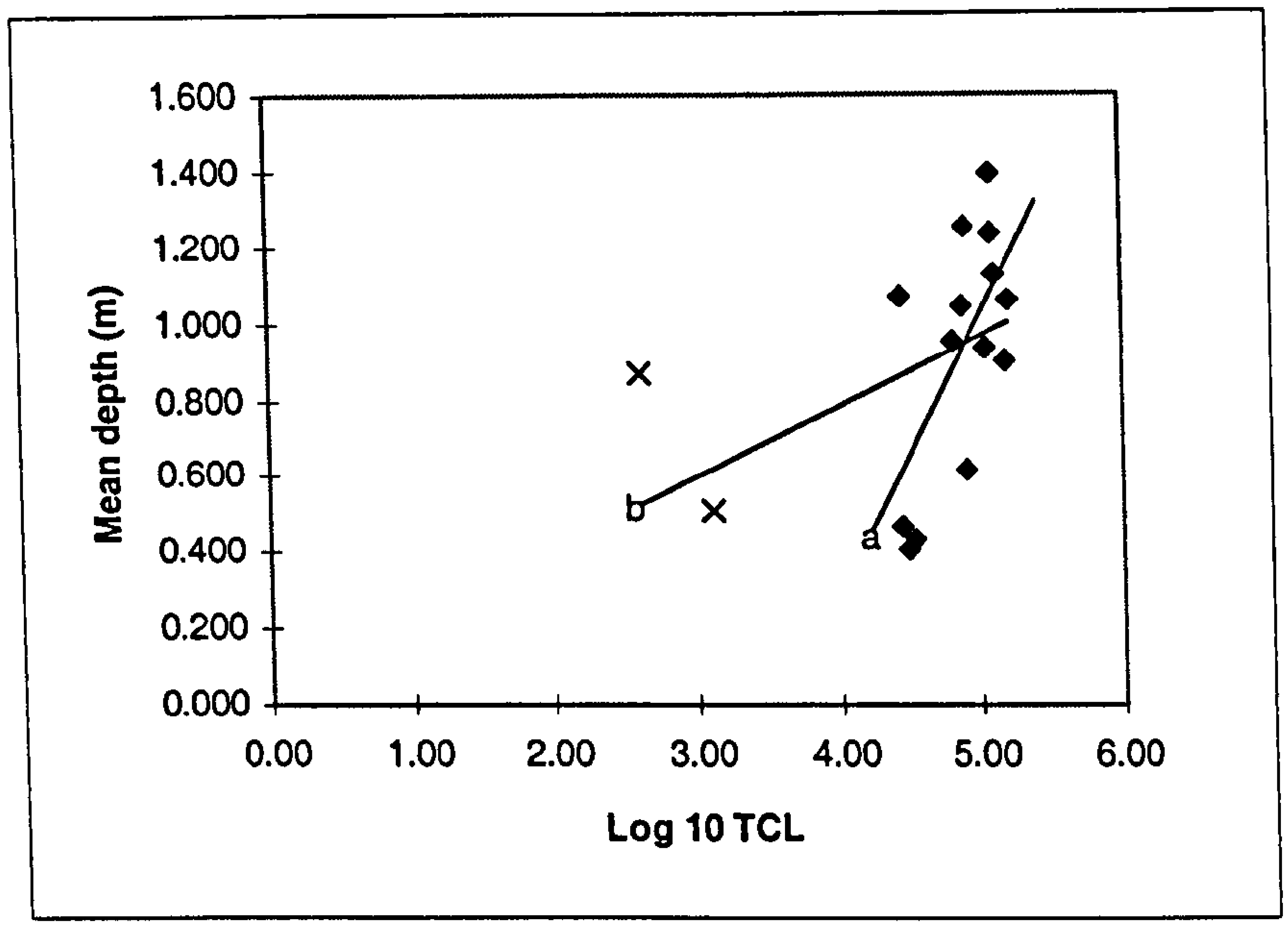


Figure 5.12 **The relationship between mean depth and TCL. a: $y = 0.75\,x^{-2.74}$ for all sites, b: $y = 0.18\,x^{0.06}$ excluding L1 and L2.**

The regression analysis of all sites (Figure 5.11) shows that when all the catchments are considered together, the relationship between width and discharge at each reach forms a strong overall relationship. However, the downstream relationships between width and TCL in each catchment may not be so consistent and it is important to consider the way in which channel geometry changes downstream through the catchments. Downstream variability in the relationship between channel width and TCL may reflect changes in the mode of river channel adjustment, and could be explained by changes in other channel dimensions that compensate for changes in width. Alternatively, variability may be indicative of other controlling factors operating at both local or catchment scales or instability within the channel.

The deviation from the regression relationship between width and TCL is explored in figure 5.13, which plots the residual values from for each site along the three rivers. The strength of the relationship between width and TCL for all the sites ($R^2 = 0.87$) was considered a strong basis for the investigation of variability around the regression line. The residuals showed a normal distribution. However, it must be recognised that the residuals are dependent upon the dataset used and the downstream variability is thus dependent upon data from only three catchments. The residual values were standardised using the procedure outlined in Chapter 4.

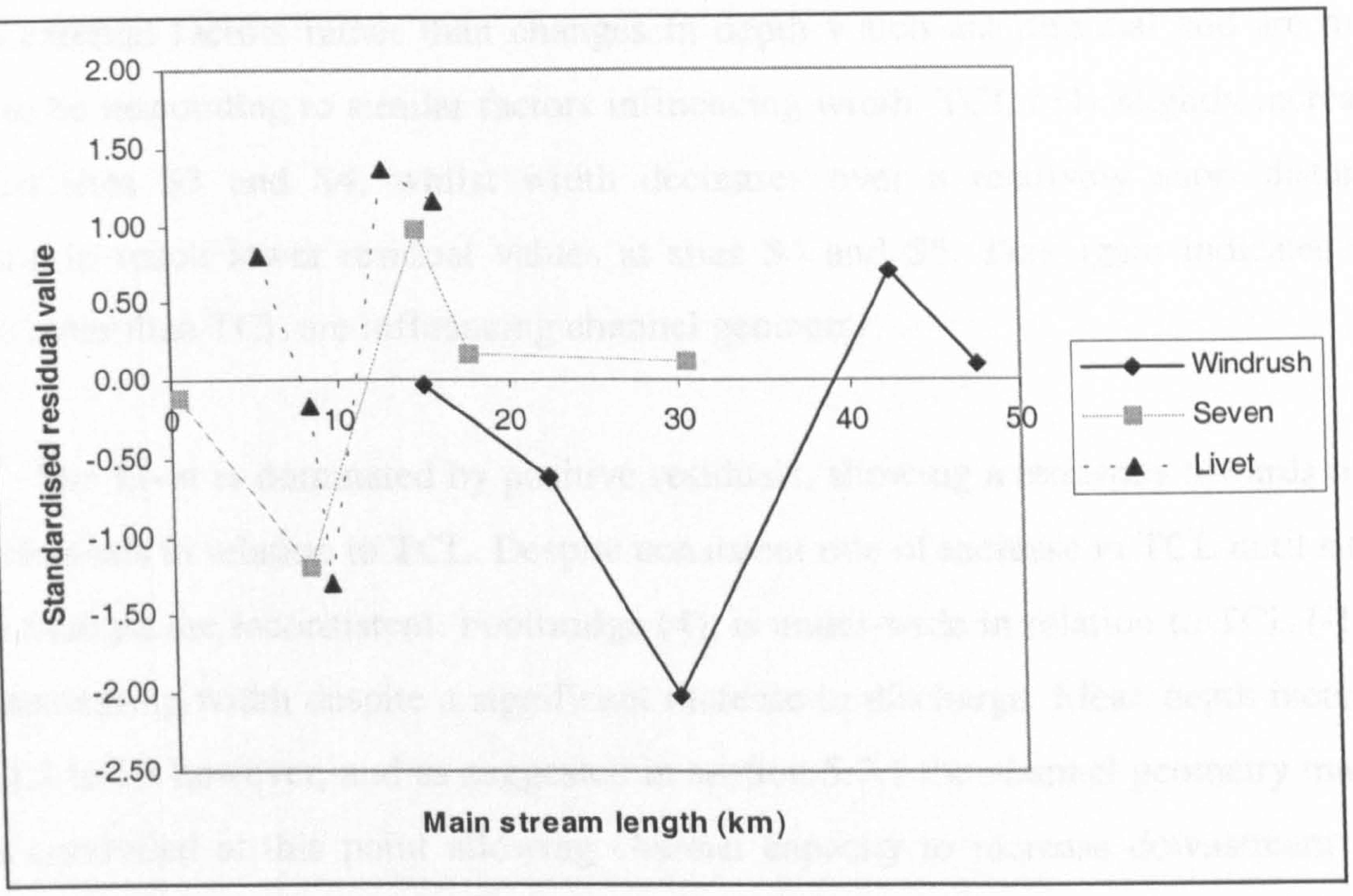


Figure 5.13 Changing residual values derived from the regression model of width and TCL for each catchment.

Table 5.9 Residual values from the regression between width and TCL for all sites from the study catchments.

	Windrush			Seven			Livet		
Site	Width	TCL	Standard Residual	Width	TCL	Standard Residual	Width	TCL	Standard Residual
1	~	~	~	2.91	0.41	-0.11	4.56	13	0.81
2	8.94	34.93	-0.03	6.88	27.93	-1.20	8.43	41.94	-0.16
3	9.86	78.99	-0.63	12.88	74.75	0.97	8.30	74.75	-1.29
4	8.33	107.52	-2.02	11.27	77.65	0.16	15.66	135.41	1.37
5	14.62	149.92	0.71	12.61	125.21	0.12	15.13	135.86	1.17
6	13.31	156.98	0.01	~	~	~	~	~	~

The downstream variability of the width - TCL relation in each river was investigated in terms of changes in the other channel dimensions, in particular channel capacity, to identify whether variability in the width discharge relationship can be explained by other forms of channel adjustment. For example changes in depth, or whether residuals are indicative of instability downstream.

The River Seven shows least variability between TCL and width with residual values of less than +/-0.5 at three of the sites downstream. The site at Bellend (S2) is under-wide (-1.20) in relation to TCL whilst Hartoft (S3) is over-wide (0.97), probably due to external factors rather than changes in depth which are minimal and are more likely to be responding to similar factors influencing width. TCL only slightly increases between sites S3 and S4, whilst width decreases over a relatively short distance, resulting in much lower residual values at sites S4 and S5. This again indicates that factors other than TCL are influencing channel geometry.

The Livet is dominated by positive residuals, showing a tendency towards over-wide channels in relation to TCL. Despite consistent rate of increase in TCL until site 4, width changes are inconsistent. Footbridge (4), is under-wide in relation to TCL (-1.29) with decreasing width despite a significant increase in discharge. Mean depth increases from L2 to L5 however, and as suggested in section 5.7.1 the channel geometry may be depth controlled at this point allowing channel capacity to increase downstream with discharge despite decreases in with. This may be due to constraints on channel width or a channel geometry that is not integrated downstream and is more dependent on local controls which are directly affecting the channel characteristics at that specific reach for example the control of valley width or slope.

In comparison, the River Windrush is relatively well represented by the regression model as width increases downstream with a steady increase in TCL shown by residual values which indicate that 2 out of 5 site have residuals of less than +/-0.5. Site four, the Fox Inn is under-wide in relation to TCL with the highest residual value of –2.02. Depth has increased enough at this point however to maintain an increasing channel capacity which is very important because it indicates that channel capacity does increase with discharge despite decreases in width. It is also clear that depth has altered indirectly with width at sites W3; where the channel is slightly under-wide depth has increased and at W5; where the channel is over-wide depth has decreased. This supports suggestions that the Windrush is depth controlled.

It is interesting to see that changes in residual values appear to follow similar patterns downstream in relation to the initial residual value. Decreases in residual values which occur in all catchments initially resulting in negative residual values of greater than –1.0 (W4, S2, L3) are followed by positive residual values of over 0.5 magnitude in each catchment. It is possible that these changes are related to downstream zoning of the river in terms of catchment conditions irrespective of scale.

The overall relationship between TCL and width was strong, but further investigation into downstream trends highlighted the importance of considering changes in other channel parameters downstream which may have adjusted to compensate for changes in width and the extent to which the catchment is integrated. Residual values are indicative of sites where TCL is less dominant in controlling channel width and other factors exert an influence on channel form. The extent to which these factors dominate downstream is important in terms of channel form adjustment. The following sections will investigate the effect of factors operating to control channel geometry at the catchment scale (5.6.3) and local controls (5.6.4)

5.6.3 Catchment characteristics

Factors which operate to control river channel form at a catchment scale, often indirectly through their influence on local variables, were discussed in Chapter 2 (sections 2.7). The drainage basin form can exert an influence on channel geometry both longitudinally and laterally. The long profile of river channels downstream represents changes in the valley slope. The degree to which valley slope and local channel gradient are linked will be considered. The lateral zones of the river channel are shown in Chapter 2 (figure 2.2, Newson, 1992a) and the degree of floodplain development and coupling between the valley sides and channel will be investigated in terms of its effect on channel form and adjustment. Finally, differences in catchment characteristics, vegetation and landuse will be briefly considered. The analysis will be based on the results from Part I of the Geomorphological survey reach scale.

Downstream changes in catchment relief are represented by the long profile, shown for each catchment in figure 5.14. Research carried out by Wheeler (1979) found a positive correlation between profile concavity and total fall, indicating that a more concave profile is associated with relative relief. This is true for the rivers shown in 5.14. The River Livet has the most concave profile, showing the biggest decrease in altitude over the shortest distance out of all the catchments. The River Seven also has a concave profile that shows most changes in the upper reaches between sites 1 and 3, then levelling off further downstream. In comparison, the Windrush shows an extremely flat longitudinal profile, which in some places is almost convex, for example between sites 1 and 3. Profiles are rarely smooth, often containing convexities which can be caused by more resistant bedrock strata, the introduction of a coarser or larger load or the effect of past events notably a fall in base-level (Knighton, 1988; 1998). The Windrush is underlain by limestone, which outcrops at Aston (W2) before the river flows onto Lower Lias clays, perhaps accounting for the convexity in river channel profile at this point. The variation between the long profiles is supported by differences in the ruggedness index, HD_d (Strahler, 1958) which is lowest in the Windrush (31.8) and increases in the other rivers to 370.8 in the River Seven and 690 in the River Livet.

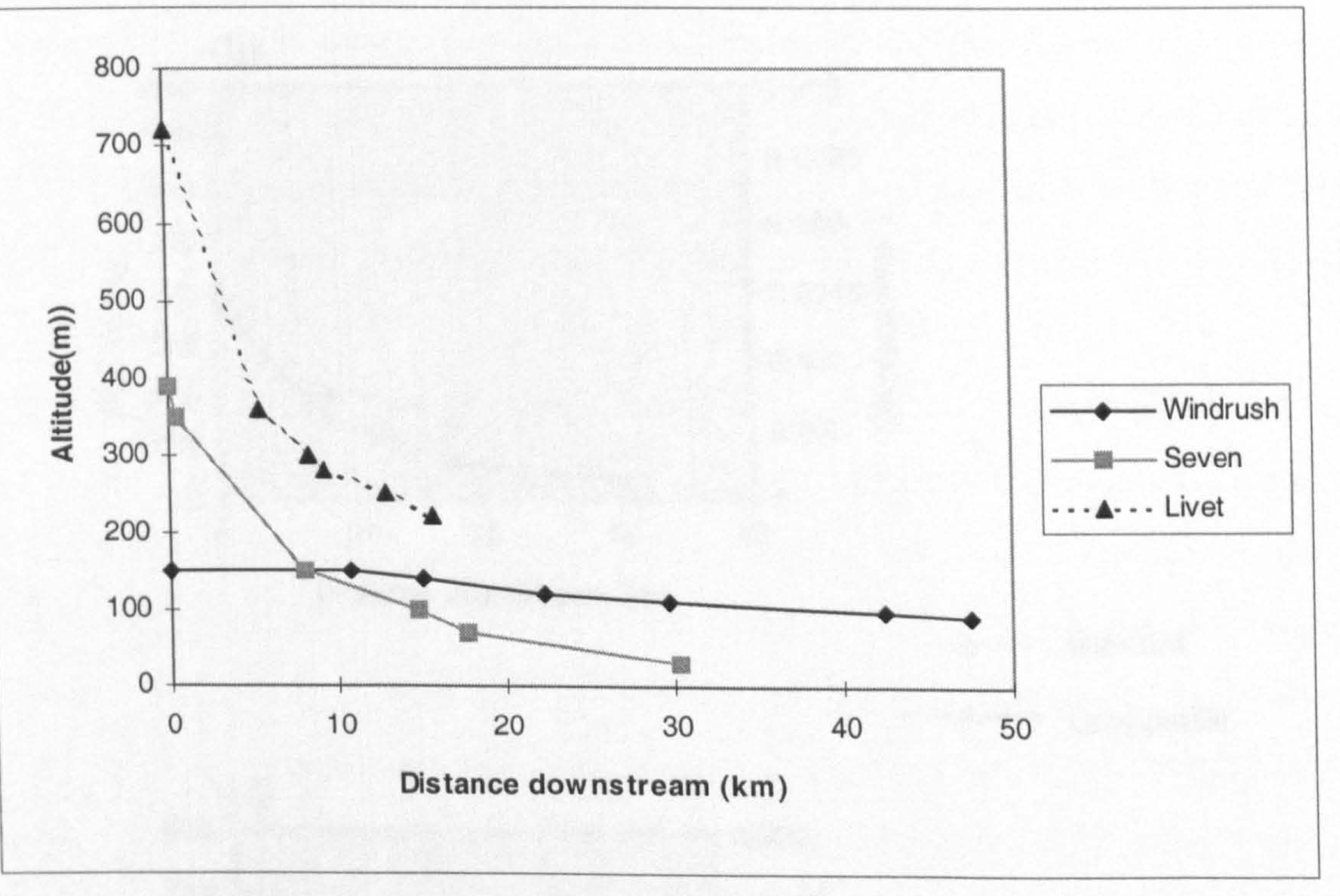


Figure 5.14 The longitudinal profiles for each catchment.

The profile form is only partly dependent on incident relief and available length and as the profile is essentially describing the downstream rate of change of channel gradient, it is important to consider the effects of changes in terms of local channel gradient variations downstream. Figures 5.15 a ,b and c illustrate changes in the local bed gradient at each site with valley slope and the extent to which they are related. The valley slope and channel gradient are closely related in the River Seven, with a big decrease between sites 2 and 3 and then much slower rate of decline. The long profile of the River Windrush shows very little change downstream that is reflected by a relatively stable channel gradient, but valley slope and gradient do not always co-vary. Valley slope decreases gradually from sites 1 to 6, but channel gradient shows more

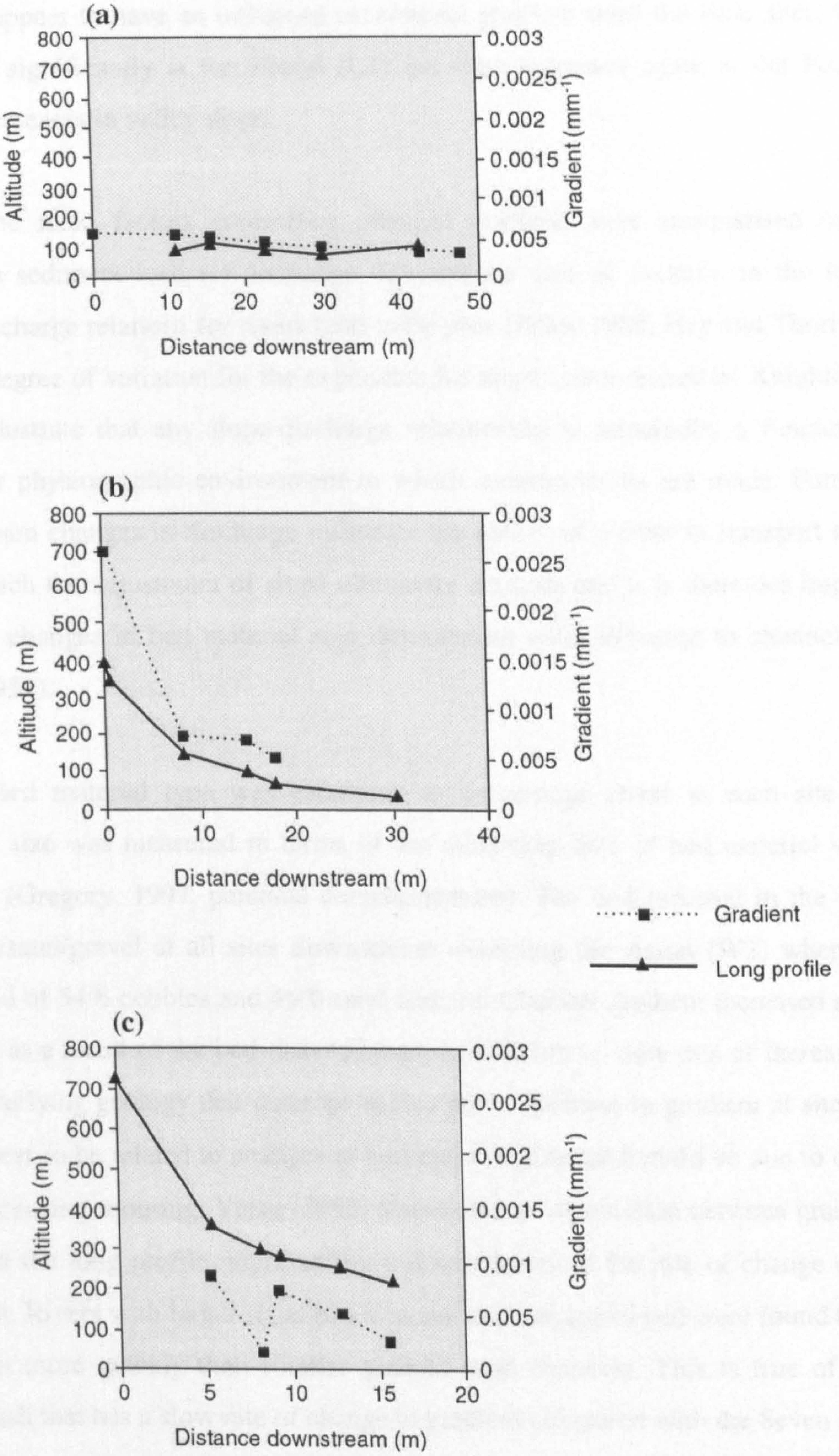


Figure 5.15 **Changes in the long profile and gradient of (a) the River Windrush, (b) the River Seven and (c) the River Livet**

variability, increasing at Aston (W2) and Asthall (W5). In the River Livet, valley slope does not appear to have an influence on channel gradient until the final sites. Gradient decreases significantly at the Forest (L2) but then increases again at the Footbridge, despite decreases in valley slope.

The main factors controlling channel gradient were summarised by Rubey (1952) as sediment load (s) discharge (Q) and the size of material in the load (M). Slope-discharge relations for rivers tend to be poor (Bray, 1982; Hey and Thorne; 1986) and the degree of variation for the exponents for slope (summarised by Knighton, 1998, p.246) illustrate that any slope-discharge relationship is principally a function of the particular physiographic environment in which measurements are made. Furthermore, downstream changes in discharge influence the ability of a river to transport sediment, upon which the adjustment of slope ultimately depends and it is therefore important to consider changes in bed material size downstream with reference to channel gradient Hack (1957).

Bed material type was estimated as percentage cover at each site and bed material size was measured in terms of the maximum size of bed material within the channel (Gregory, 1997, personal communication). The bed material in the Windrush was silt/sand/gravel at all sites downstream excepting the Aston (W2) where the bed consisted of 54% cobbles and 46% sand and silt. Channel gradient increased at this site perhaps as a result of the bed material load, in addition to slow rate of increasing TCL, and underlying geology that outcrops at this point. Increase in gradient at site W4 does not appear to be related to changes in bed material size, and could be due to other local factors causing scouring. Yatsu (1955) discovered an association between grain size and break in the long profile, representing a discontinuity in the rate of change of channel gradient. Rivers with larger sized bed material such as gravel bed were found to increase gradient more quickly than smaller grained sand channels. This is true of the River Windrush that has a slow rate of change in gradient compared with the Seven and Livet.

The Seven and Livet were both dominated by mixed bedload and the maximum size bed material used to represent channel transporting capacity, was measured by taking the average length of each axis from bed material measured over the whole reach

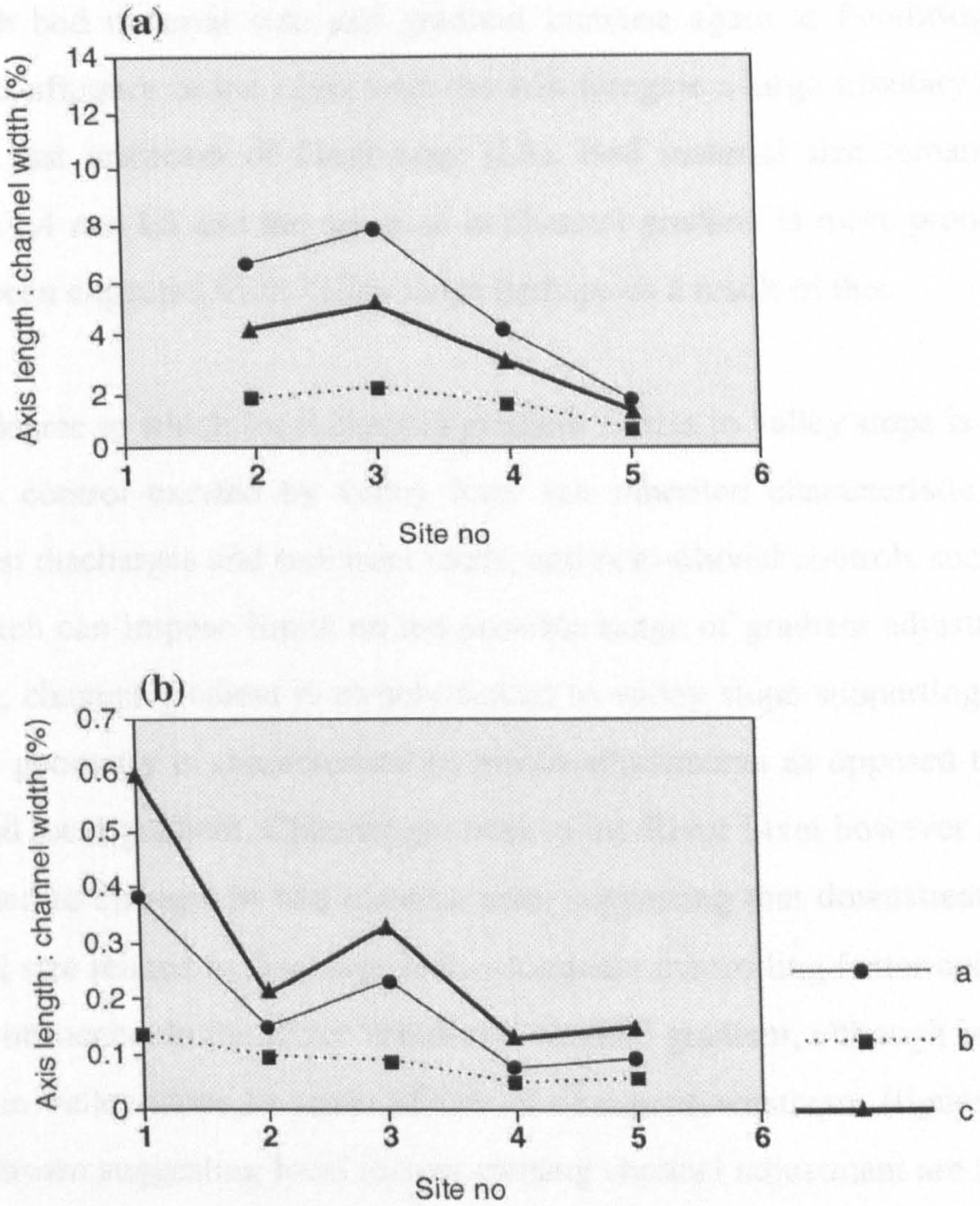


Figure 5.16 Changes in bed material size as a percentage of channel width on (a) the River Seven and (b) the River Livet

and standardised by taking average axis length as a percentage of average channel width shown in figure 5.16a and b. Maximum bed material size in the River Seven does not appear to be strongly related to gradient although at Hartoft (S3), channel gradient remains higher than would be predicted in relation to valley slope (figure 5.15b) which could be a result of increased bed material size at this site. The increase in bed material size is the result of a major tributary entering the river just upstream of Hartoft increasing discharge and sediment load downstream of the confluence. After this point bed material size decreases gradually downstream matched by decreasing channel gradient.

In comparison, the River Livet shows a strong relationship between bed material size and channel gradient (see figure 5.16b and 5.15c). The ratio of axis length to channel width decreases at Forest (L2) which is reflected in a significant decrease in gradient. Both bed material size and gradient increase again at Footbridge (L3), the result of the confluence of the Livet with the Allt Dregnie a large tributary draining the Ladder hills, just upstream of Footbridge (L3). Bed material size remains the same between sites L4 and L5 and the decrease in channel gradient is more pronounced than would have been expected from valley slope perhaps as a result of this.

The degree to which local channel gradient relates to valley slope is important in terms of the control exerted by valley form (an inherited characteristic reflecting a history of past discharges and sediment loads, and non-alluvial controls such as bedrock outcrops which can impose limits on the possible range of gradient adjustment). In the River Seven, channel gradient is closely linked to valley slope supporting the findings that channel geometry is characterised by width adjustments as opposed to changes in bed-level and local gradient. Channel gradient in the River Livet however appears to be closely related to changes in bed material size, suggesting that downstream changes in bed-material size related to discharge is the dominant controlling factor and valley slope exerts little influence. In the River Windrush, channel gradient, although broadly related to changes in valley slope in terms of rate of change downstream (figure 5.15a), does vary downstream suggesting local factors causing channel adjustment are important and that the channel geometry is depth dependent.

The transport of larger bed-material loads can not only be accommodated by an increase in slope but also through changes in channel geometry. The degree to which the channel geometry and gradient interact is crucial for determining the mode of adjustment of channel geometry. Rubey's (1952) formula implies that gradient and channel form are mutually adjusted but that, contrary to expectation, the depth:width ratio varies directly with sediment load and grain size. In an attempt to explain this anomaly, Miller (1991) investigated the mutual adjustability of gradient and cross-sectional variable depth:width ratio, using Missouri river data and concluded that the increase of the depth:width ratio could be attributed to the inverse effect of grain size on the depth:width ratio being outweighed by the direct effect of grain size on gradient, to which the depth:width ratio is positively related. That is, changes in grain size affect gradient which in turn influence changes in channel geometry. Cross-sectional variables are more dependent on the mutual adjustment mechanism than is channel gradient. The cross-sectional dimension is more likely to absorb change than is the longitudinal dimension, particularly if slope adjustment is constrained (Knighton, 1998). This seems to be the case in the River Seven where the channel appears to be controlled by width downstream and there is relatively little connection between channel gradient and geometry. Similarly, the Livet does not show a consistent relationship between slope and channel geometry downstream; rather, both appear to be mutually responding to changes in controlling variables acting in addition to discharge. Bed material appears to be strongly linked with gradient downstream that is having an indirect affect on channel dimensions. The Windrush, however shows a close relationship between gradient and the width:depth ratio indicating that the variables are interdependent.

As well as considering the influence of longitudinal changes, the lateral constraints on channel form must also be investigated downstream through the catchment. The development of the floodplain determines the degree of coupling between the channel and valley and is fundamental when considering downstream linkage between the channel and catchment downstream. The extent to which the channel is confined may influence the mode of adjustment within the channel. For example, where a channel is confined, particularly in small headwater reaches, deepening may be the dominant change and adjustments to planimetric properties become somewhat limited (Anderson and Calver, 1977). Most channels are characterised by intermittent links which are neither strongly coupled nor strongly buffered, but intermittently coupled, the case with the Seven and Livet.

The catchment conditions were assessed at each site using the Part 1 Geomorphological Survey Reach Scale the results of which are shown in table 5.10. It is difficult to interpret the results in terms of whether the floodplain exists or not at each site and its effect of channel geometry. Initial observations do not indicate an overall relationship between the introduction of the floodplain and channel geometry, suggesting that the relationships between the channel and floodplain are complex and varied, not least because of the different ways in which floodplains are formed. However several trends can be observed from the Table 5.10 in relation to changes in

Table 5.10 **Catchment characteristics**

	1	2	3	4	5	6
WINDRUSH	*Naunton*	*Aston*	*New Bridge*	*Fox Inn*	*Asthall*	*Minster*
Floodplain	>10 (A)	None	> 10 (A)	> 10 (A)	> 10	>10
Riparian buffer strip	Continuous	< 1	<1	n	Continuous	n
Terraces	n	n	n	n	n	n
Vegetation	Pasture	Arable, deciduous	Arable	Pasture	Pasture	Mixed deciduous, grass
Landuse LH	Arable	Woodland	Arable	Grassland	Pasture	Grass field
Landuse RH	Woodland	Pasture	Arable	Grassland	Pasture	Woodland
Valley form	Shallow vee	Deep Vee	Shallow vee	Shallow vee	Shallow vee	Woodland
Valley width (m)	100	500	538	213	400	263
SEVEN	*Rosedale*	*Bellend*	*Hartoft*	*Lower Askew*	*Normanby*	
Floodplain	n	1-5	n	5-10	>10	
Riparian buffer strip	n	n	n	n	n	
Terraces	n	n	n	n	n	
Vegetation	Moorland	Pasture	Pasture	Pasture	Pasture	
Landuse LH	Moorland	Grassland	Forestry	Pasture	Vegetated	
Landuse RH	Moorland	Grassland	Moorland	Pasture, forestry	Road	
Valley form	Shallow vee	Deep vee	Deep vee	Shallow vee	Concave bowl	
Valley width (m)	50	125	25	250	425	
LIVET	*Suie*	*Forest*	*Footbridge*	*Bridge*	*Distillery*	
Floodplain	1-5 widths	>10	5-10	n	>10 widths	
Riparian buffer strip	n	n	n	n	n	
Terraces	Continuous	Fragmentary	Continuous	n	Indefinite	
Vegetation	Moorland/pasture	Coniferous	Pasture	Pasture,deciduous	Pasture	
Landuse LH	Moorland	Moorland,grassland	Vegetated	Woodland, grassland	Pasture	
Landuse RH	Moorland	Forestry	Vegetated	Woodland, grassland	Pasture	
Valley form	Deep vee	Shallow vee	Shallow vee	Deep vee	Deep vee	
Valley width (M)	100	600	100	100	200	

channel geometry. Contrary to expectation, at those sites where there is no floodplain, for example Bridge (L4), Aston (W2) and Hartoft (S3) channel width increases significantly. This could be because the channel is contained by the vee-shaped valley causing maximum erosion of channel banks as the water is retained within the channel during bankfull conditions.

The River Windrush is connected with a floodplain at all sites apart from the second site at Aston (W2), indicating that the floodplain is established even in the headwaters a legacy of the palaeo conditions (Dury,1955). Naunton was the first site where measurement could take place on the River Windrush despite the fact it is so far downstream because of the underlying geology producing dry valleys and ephemeral flow in the headwaters. As the channel flows on to Lias clays the floodplain becomes well established. In comparison, the River Seven shows an interesting pattern where a floodplain appears to develop as the channel flows off the moorland but then disappears again as the valley narrows, before there is a re-development of the floodplain as the river flows out onto the Vale of Pickering. The existence of the floodplain in the upper reaches is important in terms of the river system as a whole. The classification of the upland floodplain, observed at S2 has been the subject of some discussion with reference to its functional definition (Petts, 1998). The River Livet also appears to be connected to a floodplain in the upper reaches.

The coupling of channel and valley forms was investigated further by comparing channel and valley widths and how the relationship changed downstream, shown in figure 5.17 (a, b and c). The Windrush shows a close relationship between channel width and valley width that indicates that the valley form is exerting an influence on channel form. Dury (1964), observing changes in channel pattern in relation to valley form, used the River Windrush as an example of an underfit river where the current river is confined within a meandering valley. The underfit channel flows across a buried channel which was much larger than the present day, formed as a response to low sea levels during the later part of the Quaternary (Gregory and Walling, 1973). Meander wavelength of the stream is lower than that of the valley and this could also effect channel geometry, which appears to be linked to valley form. The River Livet appears to broadly follow the trends in valley form until Bridge (L4) where the channel width increases despite a sharp decrease in valley width.

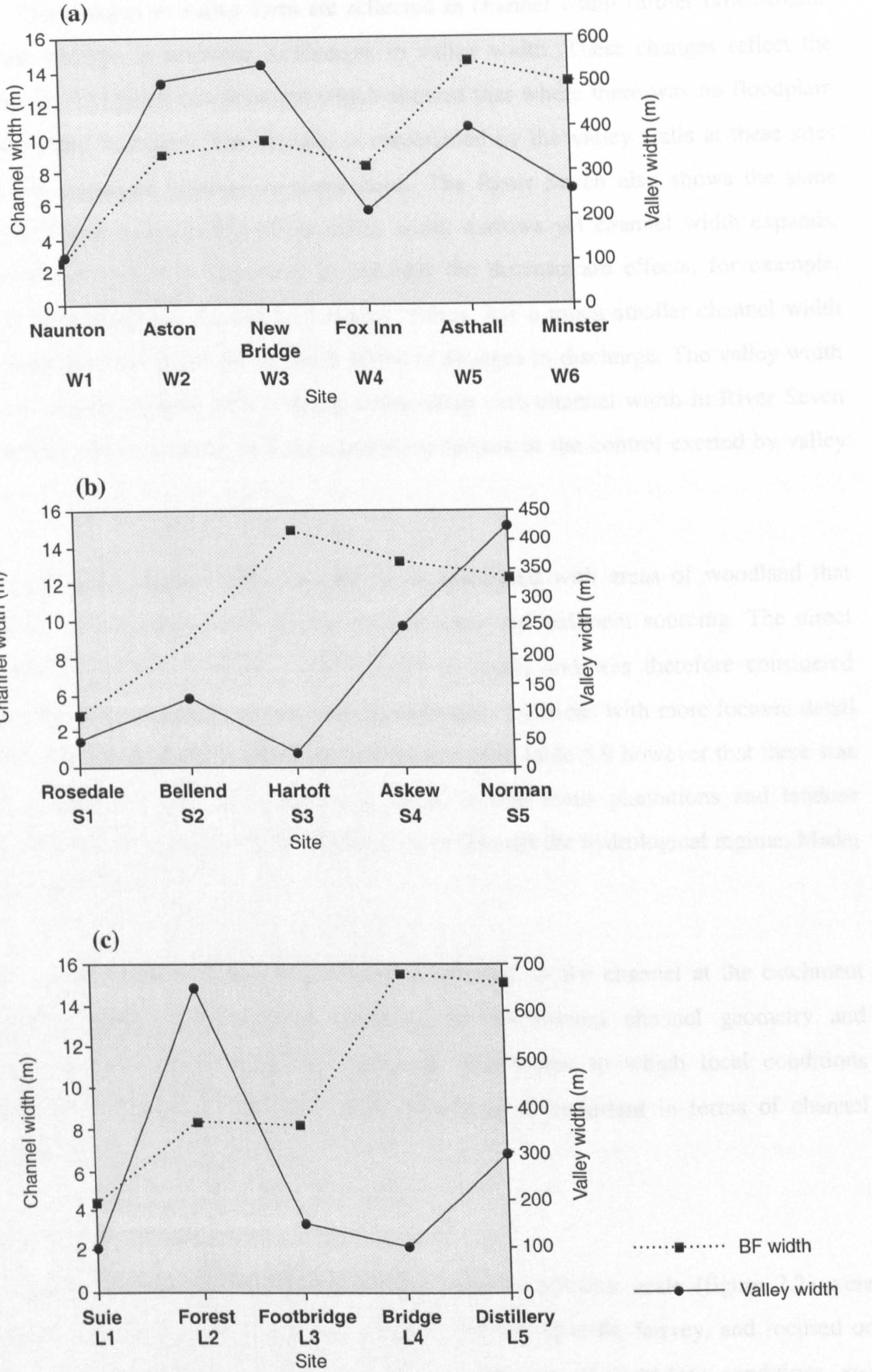


Figure 5.17 **Changes in bankfull channel width and valley width downstream on (a) the River Windrush, (b) the River Seven and (c) the River Livet.**

The changes in valley form are reflected in channel width further downstream, however, perhaps in response to changes in valley width. These changes reflect the findings on floodplain development which showed that where there was no floodplain channel width increased. The channel is constrained by the valley walls at these sites width has expanded contrary to expectation. The River Seven also shows the same phenomenon at Hartoft (S3) where valley width narrows yet channel width expands. Where this occurs it is important to consider the downstream effects, for example, Askew (S4) located at the end of a narrow valley, has a much smaller channel width than Hartoft which is not just a direct effect of changes in discharge. The valley width does not appear to have such a strong relationship with channel width in River Seven and which may be a result of local controlling factors or the control exerted by valley slope.

The vee shaped valleys tended to be associated with areas of woodland that could be a factor in determining runoff processes and sediment sourcing. The direct effect of vegetation, however, was difficult to assess and was therefore considered indirectly as an integrated part of overall catchment conditions with more focused detail at the reach scale (section 5.6.4). It was evident from table 5.9 however that there was little change in width after significant areas of coniferous plantations and landuse changes have an indirect effect on channel form through the hydrological regime, Madej and Ozaki (1996).

The longitudinal and lateral controls exerted on the channel at the catchment scale are clearly an important influence on downstream channel geometry and adjustment at a reach must be considered. The extent to which local conditions counteract or promote catchment scale influences is important in terms of channel adjustment.

5.6.4 Local controls

Local factors affecting the channel at the reach or corridor scale (figure 2.2) were recorded in Part II of the Geomorphological Section Specific Survey, and focused on boundary conditions and vegetation. The importance of boundary conditions was discussed in Chapter 2, section 2.5.2 that highlighted the importance of considering bank strength in terms of channel width adjustment. An average value of shear strength was taken from ten samples on both banks of each section and this was used to provide an overall mean for each site. The results are shown in figure 5.18(a, b and c). The relationship between the percentage fines and shear strength is in general positive where increasing silt/clay in the channel banks (M) results in an increase in shear strength.

The highest silt/clay percentage (M) occurs in the River Windrush, rising to over 80% at the final three sites where the river is flowing over Lias Clays. The shear strength is comparatively low however, with values of between 20-30 kPa associated with M values of 50-60 % implying that factors other than M are controlling bank strength, for example the degree of wetting or tensile strength from roots of vegetation. It is impossible to identify a strong dependence of channel width on shear strength in the River Windrush. Width increases significantly at Asthall despite an increase in bank strength suggesting that bank erosional processes must be different at this site from the other sites, which is supported by the two-stage channel form at this point.

In the River Livet, there is a closer relationship between shear strength values and percentage silt/clay. Bank strength, is lowest in the River Livet which could explain the tendency towards over-wide channels, indicated by the residual values. However, downstream changes in bank strength are relatively small and do not correspond with downstream changes in channel width or area (figure 5.8a). The lowest shear strength and M values are found at Bridge (L4) where width was greatest, but the values at Footbridge (L3) were only slightly different yet width was much smaller, suggesting that bank strength is not a dominant controlling factor downstream.

In the River Seven, bank strength and M decrease from the source to Hartoft, inversely related to width which increases to a maximum at Hartoft (S3), suggesting that the bank materials and strength are influential on channel width adjustment. M

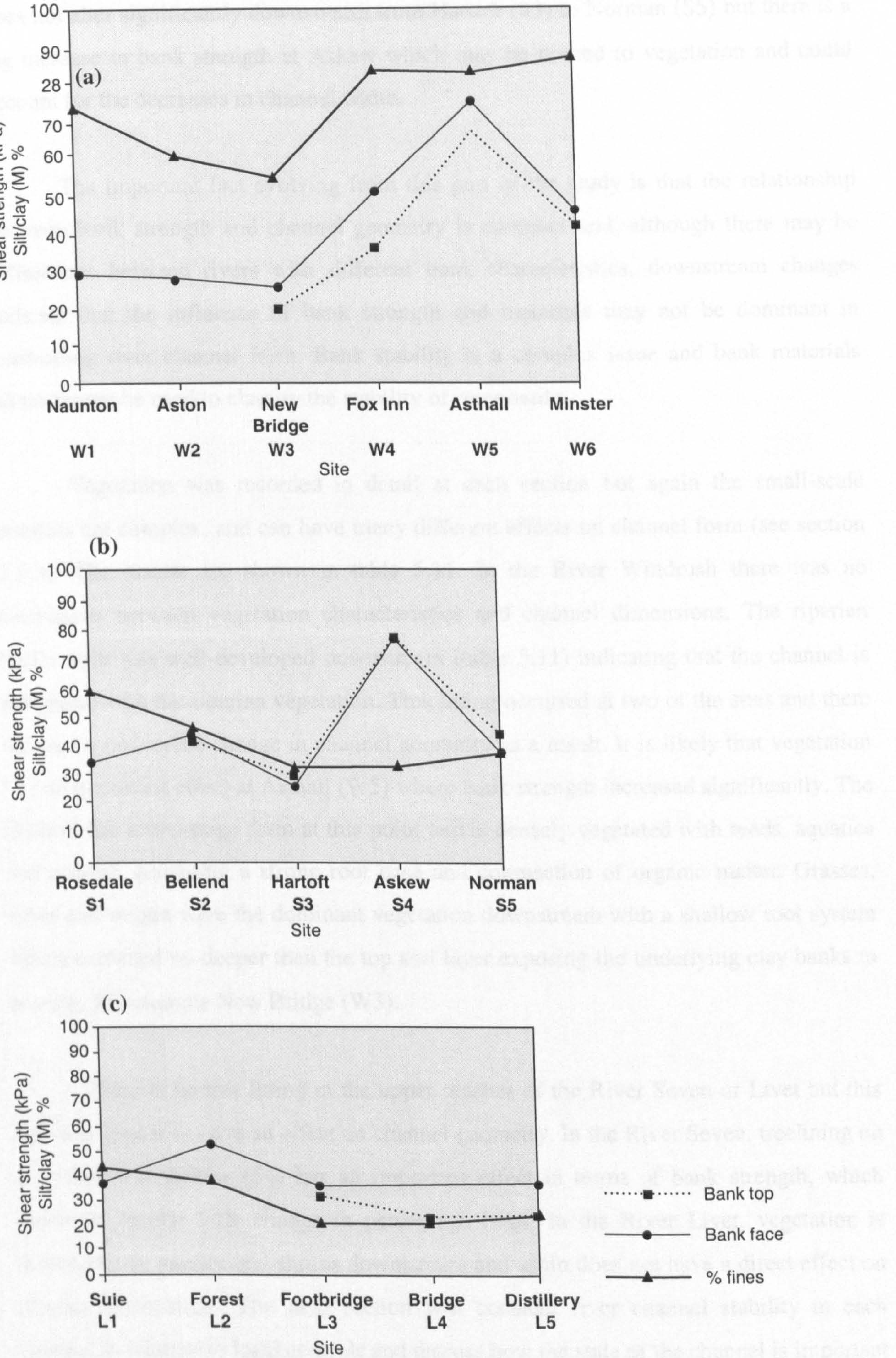


Figure 5.18 **Changes in channel boundary conditions downstream in (a) the River Windrush, (b) the River Seven and (c) the River Livet**

does not alter significantly downstream from Hartoft (S3) to Norman (S5) but there is a big increase in bank strength at Askew which may be related to vegetation and could account for the decreases in channel width.

The important fact evolving from this part of the study is that the relationship between bank strength and channel geometry is complex and, although there may be differences between rivers with different bank characteristics, downstream changes indicate that the influence of bank strength and materials may not be dominant in controlling river channel form. Bank stability is a complex issue and bank materials alone cannot be used to classify the stability of river banks.

Vegetation was recorded in detail at each section but again the small-scale controls are complex, and can have many different effects on channel form (see section 2.5.3). The results are shown in table 5.11. In the River Windrush there was no correlation between vegetation characteristics and channel dimensions. The riparian buffer strip was well-developed downstream (table 5.11) indicating that the channel is integrated with the riparian vegetation. Tree lining occurred at two of the sites and there was not a noticeable change in channel geometry as a result. It is likely that vegetation had an important effect at Asthall (W5) where bank strength increased significantly. The channel has a two-stage form at this point and is densely vegetated with reeds, aquatics and grasses, providing a strong root base and compaction of organic matter. Grasses, reeds and sedges were the dominant vegetation downstream with a shallow root system which extended no deeper than the top soil layer exposing the underlying clay banks to erosion, for example New Bridge (W3).

There is no tree lining in the upper reaches of the River Seven or Livet but this does not appear to have an effect on channel geometry. In the River Seven, treelining on both banks at Askew (S4) has an important effect in terms of bank strength, which increases despite little change in percentage fines. In the River Livet, vegetation is dominated by grasses and shrubs downstream and again does not have a direct effect on channel dimensions. The next section will consider river channel stability in each channel in relation to local controls and discuss how the state of the channel is important at a reach scale in determining changing channel geometry.

Table 5.11 Table showing vegetation characteristics at each site

	Type		*Tree age*		*Diversity*		*Lining*		*Density*	
Windrush	LH	RH	LH	RH	LH	RH	LH	RH	LH	RH
Naunton	3,4	3,4								
2	2,3	2,3								
3	3	2,3								
Aston	2,5,6	6	2	2	3	3	D	D	Continuous	
2	6	2,3,6	1,2,3		3		M	D		Continuous
3	2,3, 6	2,3,6	3	1	3	2	M	D	Broken	Single
New Bridge	2,3	2,3								
2	2,3	2,3								
3	3	2,3								
Fox Inn	2	2								
2	2	2,3								
3	1	2								
Asthall	2	2								
2	2	2								
3	2	3								
Minster	2	2,6		3		3		M		Broken
2	2	2,6		3		3		M		Broken
3	2	2,6		3		3		M		Broken
Seven										
Rosedale	2,4	2,4								
2	2,4	2,4								
3	2,4	2,4								
Bellend	n	1,4,6,								
2	1,6	n								
3	1,2	1,3,								
Hartoft	2,4,6	3	3		2		M		Continuous	
2	2,4,6	3	3		2		M		Continuous	
3	2,4,6	3	3		2		M		Continuous	
Askew	1	1,2,5,6,		1,2,3,		3		D		Broken
2	1	1,5,6,		2		2,3	D	D	Broken	Continuous
3	1	1,5,6,		2,3,		2	D	D	Broken	Continuous
Norman	2	1,2,6,		2		1		D		Broken
2	1	1,2,6		2		1		D		Broken
3	5,6	1,6	2	2	1	1	D	D	Continuous	Broken
Livet										
Suie	2,4	2,4								
2	2,4	2,4								
3	2	2,4								
Forest	2	2								
2	2	2								
3	2	2								
Footbridge	2	2								
2	2	2								
3	2	1,2								
Bridge	1	2,3,4,5,6	1,2,3,	1,2,3	2	2	D	D	Broken	Broken
2	1,6	2	2	2,3	3	3	C	D	Continuous	Continuous
3	1,2,6		3		2		D		Broken	
Distillery	2,6	1,2,6	2	2	2	1	D	D	Broken	Continuous
2	3	2,6		2		1	n	D		Continuous
3	1		3		1		D		Broken	

Key

Type
1 None
2 Grasses and FloraD
3 Reeds and sedges
4 Shrubs
5 Saplings
6 Trees

Tree type
M Mixed deciduous and coniferous
Deciduous
C Coniferous
n None

Tree age
1 Young
2 Mature
3 Old

Diversity
1 1 species
2 2-5 species
3 5+ species

5.6.5 River channel stability

The final stage of analysis assesses river channel stability at each site and the relationship between river channel geometry and current channel state. Geomorphic indicators recorded in Part II of the Geomorphological Survey were used to observe river channel stability at each section and the results were used to make an overall assessment for each site shown in table 5.12. The findings from the results are then compared with the residuals obtained for each catchment using the national regression model.

The River Windrush was fairly inactive and did not show any signs of extreme erosional activity but tended towards aggradation as the dominant process especially at the last two sites. Aston (W2) was a unique site on the Windrush, with a high W:D ratio and signs of erosion during peak flow at section one, and characteristics associated with woodland areas such as coarse woody debris associated with localised scour. At the last two sites, the build up of silt was evident with aquatic growth, mid channel bars and large amounts of accumulated sand and silt at the edges of the channel. Fox Inn (W4) was the only site where erosion was clearly occurring, with scouring of bank material from underneath the top soil layer and subsequent collapse of the root based clumps into the channel. The residual values from the regression analysis of width and TCL from sites from the three catchments, for the River Windrush can be linked with changes in the dominant processes downstream. Fox Inn is under-wide (-2.02) and the erosion at this site indicates some processes operating to increase channel width.

The River Seven contrasted with the River Windrush and was found to be actively eroding downstream. Bellend (S2) is most actively eroding, with bank undercutting and evidence of slumping. The channel has broken treelining at this point that could have constrained channel width, as the roots are exposed and the trees were bent towards the channel. This is reflected by the negative residual value at this point and erosion may depict a tendency for the river to expand. At Hartoft (S3), width is greatest, but there was evidence of stability, with weed growth on the boulders, little erosion and no clear signs of channel change. The river is over-wide at this point compared with the final two sites that have small residual values. Askew (S4) also demonstrates signs of erosion (undercutting and exposed tree roots) despite the fact that the bank shear strength increases significantly at this point.

Table 5.12 **Results of the stability survey for (a) the River Windrush (b) the River Seven and (c) the River Livet**

(a) River Windrush

Site	*Undercut*	*Roots exposed*	*Tension Cracks*	*Detailed description*	*General synopsis*
Naunton	n	n	O	Channel is migrating, some slumping occurring	Stable
Aston	n	n	n	Some erosion at section 1, completely undisturbed, evidence of erosion during peak flood events	Stable/ Eroding dormant
New Bridge	n	n	n	Aggradation evident in mid channel bars and dunes	Stable
Fox Inn	y	n	n	Banks are eroding (5-20cms) under the top soil layer which is secured by grass roots, unstable top soil collapses into channel as root based clumps which are remaining in the channel.	Eroding dormant
Asthall	n	n	n	Two-stage channel, slumped blocks, build up of aggregates and rootbased clumps on LHS, revegetation, silts build up	Aggrading
Minster	n	n	n	Localised points of erosion, silt build up extreme, channel much shallower in last decade (source: local residents), revegatation on RHB.	Aggrading

(b) River Seven

Site	*Undercut*	*Roots exposed*	*Tension Cracks*	*Detailed description*	*General synopsis*
Rosedale	y	y	n	Incised moorland channel in early stages of development, evidence of erosion and banks undercut	Eroding
Bell end	y	y	y (3)	Erosion occurring on RHB, banks undercut (0.1-0.3m) close to base, slumping evident and tension cracks on RHB.	Eroding active
Hartoft	n	n	n	Channel relatively stable, dominated by large boulders, some signs of erosion, but banks are not undercut	Stable
Askew	y	y	y (3)	Erosion evident at all sections, tension cracks and slumping also evident at section 3.	Stable, eroding
Norman	y	y	F	Erosion evident at all sections, with tension cracks, graduated banks and slumped block indicating mass movement.Channel deep at this section but more stable d/s.	Eroding

(c) **River Livet**

Site	*Undercut*	*Roots exposed*	*Tension Cracks*	*Detailed description*	*General synopsis*
Suie	y	n	O (1,3)	Upland channel, erosion dominant, banks undercut (0.05-0.15m) close to base, Further d/s extreme erosion.	Eroding
Forest	y	n	n	Bank collapse evident, root based clumps within the channel, cobble bar. Terraces suggest active migration (photo ?)	Active stability
Footbridge	y	y	O (3)	Undercut is significant occurring to a height of 0.45m and a depth of 0.55m, fluvial deposits are washing out from underneath the topsoil, held in place by roots.	Active erosion
Bridge	y	y	O (1, 3)	Evidence of slumping and undercutting but erosion slow	Stable
Distillery	n			Localised erosion and aggradation but no process dominant.	Stable

It is possible that treelining has increased bank strength, but bank erosion and slumping associated with the increase in bankfull height seen at this site associated with the development of the floodplain, has continued to occur. At Norman (S5) the river is deeply incised into the valley fills and the banks were over 4m in height. Further downstream (inaccessible for measurement), the channel appeared more stable and it is possible that the reach selected was isolated. However, slumping and bank instability at the reach suggested that the channel was unstable at this point.

The River Livet showed signs of erosion in the upper reaches becoming more stable downstream. In the upper reaches the channel was very high energy and erosion during peak flood events was clear. Bank erosion was also clear at Forest (L2) and Footbridge (L3). At both sites the terrace system suggested that channel was actively migrating, although the decrease in channel width at forest (L3) and the residual value point to a tendency towards increasing width, as both banks demonstrated signs of erosion compared with the Forest (L2) where erosion was evident on one bank only and gravel bars suggested active stability and channel migration. The final sites were stable, with localised erosion. It is possible that vegetation has had a stabilising effect on the channels. Peak flood events are crucial to this river system and are not represented by Total Channel Length. The geomorphology is determined by extreme events related to snow melt and this is evident at all sites. The decrease in width in the River Livet is probably a result of the floodplain which allowing over-bank flow which prevents erosion of the channel evidenced at Bridge (L4) where the river is constrained by valley form. The results from the stability survey were found to corresponded with the findings from the analysis of downstream geometric parameters and observed dominant mode of adjustment. This indicates that stability can be confirmed by catchment wide measurements of geomorphological parameters.

To put the findings from the catchment into context of the national study and test to what extent the national regression model can be used to predict likely direction of change residual values for the rivers Windrush, Seven and Livet were computed using the national regression model. The data used to calculate the residuals are shown in table 5.13.

Table 5.13 **Residual values calculated using the national model of 124 sites ($y = _{0.54}Qd^{0.42}$) for the study three catchment sites to test the findings from the national model.**

River	Station	Width	Log10 w	Qd	Log 10 Qd	Predicted Log10 w	Residuals	Standard residuals
Windrush (Minster)	39076	13.31	1.12	11.23	1.05	0.98	0.14	**1.13**
Seven (Normanby)	27057	12.62	1.10	47.22	1.674	1.24	-0.14	**-1.12**
Livet (Minmore)	8011	15.13	1.18	31.65	1.5	1.17	0.01	**0.08**

The residual values derived for the three river reaches in each catchment using the national model were found to reinforce the findings from the national study. The residual values for the River Windrush are positive representing over-wide channels, which based on the findings from the national study are likely to decrease in channel width through deposition. The Windrush bore similarity in channel behaviour to the chalk rivers in class 5 and was ground water dominated, with a sand gravel bed and silt clay bank. The river was classified as aggrading at both Asthall and Minster with silt build up both in the centre and sides of the channel. A two-stage channel had developed at Asthall suggesting that the channel has adjusted to lower flows. At both sites there were signs of channel re-adjustment, but the rate of change may be slow. This type of behaviour was similar to that observed in rivers in class 5 and demonstrated inactivity or deposition. TheWindrush was closely related to the catchment form and it is suggested that channel form may be a legacy of past climatic events.

The residual value for the River Seven at Normanby (27057) was indicating an under-wide channel with a tendency towards erosion and channel enlargement. The dominant mode of adjustment in the River Seven was width controlled and evidence of erosion was found downstream throughout the catchment. The field evidence at the site itself showed a deeply incised cross-section characterised by silt-sand bank materials and a mobile cobble bed. The channel was showing signs of erosion, with tension cracks, slumping and graduated banks, similar to the River Weaver (90). It was noted however that the channel appeared to be more stable downstream suggesting that instability is localised and less severe at other points in the reach, similar to rivers in class 2. Bedrock was not a feature in this channel, but valley slope was shown to have a strong relationship with local bed gradient which maybe constraining depth adjustment.

The River Livet was closest to the model line (0.08) predicted from the findings of the model to demonstrate a stable channel form. The integrated adjustment of width depth and gradient downstream in response to sediment and discharge loads may represent a channel free to adjust, demonstrating active stability. The Livet at Minmore showed signs of localised erosion and deposition but no process was dominant. The river at this point was developed on the floodplain and on the basis of evidence from the rest of the catchment the river channel could be classified as actively stable.

5.7 Summary

The catchment study clearly demonstrated the importance of understanding the mutual adjustment of cross-sectional parameters which are commonly considered in empirical studies as separate elements of the system. Miller (1991) stressed the importance of considering the mutual adjustment of channel variables. This was echoed by Darby (1994) who highlighted the relationship between changing width and depth throughout the adjustment sequence.

The relationships between w, d and dmax suggest that *modes of adjustment* dominated in each catchment dependent on controlling factors operating at both catchment and local scales. In the River Seven, adjustment appeared to be width controlled, in the River Windrush adjustment was depth controlled and the mutual adjustment of width and depth downstream was clearly evident in the River Livet. The changes in channel width and depth and resultant channel shape were also dependent on adjustment of local channel gradient. The differences were surprisingly clear in each river.

Gradient and W:D ratio were closely related in the River Windrush suggesting that bed-level changes were influencing changes in channel shape downstream or vice versa. Darby (1994) found that depth changes were more sensitive to gradient than width changes and this was clearly reflected in the River Windrush where adjustment appears to be depth controlled. In the River Seven, however, gradient steadily decreased downstream and did not appear to be related to W:D ratio which was closely linked with change in width. There was a close relationship between downstream gradient and the longitudinal profile suggesting that the valley slope is exerting a strong influence on changes in local channel depth and bed-level changes. This was supported by constant maximum depth downstream that suggests a maximum level of incision. In the River Livet, the mutual adjustment of width, depth and gradient were clearest and there did not appear to be a dominant mode of adjustment, rather a complex sequence of adjustment downstream. There appeared to be a spatial lag effect in the response of changes in channel shape (W:D ratio) representing channel efficiency to changes in channel gradient.

The relationship between d and dmax was also found to vary significantly between catchments and appeared to be indicative of the extent of depth variability downstream. For example, in the River Livet d and dmax showed parallel increases downstream suggesting an overall increase in depth. In the River Seven, dmax remained constant downstream and incision appeared to be at a maximum suggesting thatbed level change may be limited. This was confirmed by a well-developed long profile, suggesting that bed slope downstream may be limiting depth adjustment. The River Windrush in further contrast, showed variation between d and dmax changes downstream.

The stability of the channels at a reach could be related to the adjustment of channel geometry. The River Livet showed active stability downstream, which was indicated by active width, depth and slope adjustment at each site. The effects of adjustment in channel geometry were integrated downstream, with changes in width interacting with changes in depth and channel gradient in response to changing bed loads. Erosion was an important feature at several sites and the importance of peak flow events may be influential in width adjustment, although counteracted by changes in depth.

The River Windrush appeared to be aggrading downstream, with little or no bank erosion and evidence of siltation. This supports suggestions that adjustment of channel form in relation to discharge is depth controlled. Finally, the River Seven directly contrasting with the River Windrush was actively eroding downstream reflective of width adjustment. Erosion was dominant, but at some sites downstream the river appeared to be actively migrating.

The findings from the catchment stability study are represented by the residual values computed for each river using the national regression model. This confirmed that residual values are broadly representative of geomorphological stability and also highlighted the importance of observing downstream trends in channel adjustment related to controlling factors in identifying the possible reasons for instability.

CHAPTER 6

CONCLUSIONS AND RECOMMENDATIONS FOR RIVER MANAGEMENT

6.1 Research overview

The aim of this research was to investigate the use of residual values from a downstream hydraulic geometry model to determine river channel stability and sensitivity to change. The literature review and a detailed questionnaire aimed at practitioners undertaking river restoration for the Environment Agency, highlighted the lack of geomorphological input into current design methods. The method of designing channel dimensions for river restoration still remains unclear with little structured guidance for geomorphological input. The term restoration in itself implies a return to a previous channel form but difficulty lies in whether the design of cross-sectional dimensions based on a palaeo channel model is related to current hydrological and geomorphological conditions. It is clear from this research that changes in variables at local and catchment scales are important in controlling cross-sectional adjustment. On the basis of this, design of river channels for restoration, flood alleviation or diversion requires an understanding of adjustment at a reach and application of geomorphological knowledge to improve on current design methodologies.

Channel geometry discharge equations (such as Hey and Thorne, 1986) are still used as a method for predicting channel dimensions with the advantage of relating the channel to current flow records. However, the use of such conventional downstream hydraulic geometry equations for the design of channels has contributed to the need for restoration as a result of geomorphological degradation (Brookes, 1988). The variation around the model was shown in Chapter 4 to over-predict bankfull channel width by up to 23m and under-predict by up to 13m. These are extreme cases, but within the standard error of a normal distribution of standardised residuals the mean difference in width was above 3m for both positive and negative residuals (for S.E. 0.5-1.0).

It has been suggested that such variation in downstream hydraulic geometry models, shown by the difference between the observed and predicted width, may be useful in assessing the degree of instability within the channel and the likely direction of adjustment. However, there has been little research to establish whether this is the case and this research developed a downstream hydraulic geometry model based on a large dataset of semi-natural rivers to investigate the geomorphological significance of residual values. The residuals were divided into five classes based on the standard error bars 1.0 to –1.0. Initial analysis was undertaken to investigate the hydrometric and geometric properties of rivers to assess whether residuals were representative of rivers with similar characteristics. This was followed by a more detailed field investigation of a sub-set of fifty rivers to evaluate river channel stability through geomorphological surveys.

The findings of the national study were limited to assessing rivers at a reach scale. As stated above, the cross-sectional dimensions at a reach are affected not only by local factors but also catchment scale controls. The state of the river channel upstream and downstream is important in terms of adjustment at a single reach, primarily because of the supply and transport of sediment which determines the adjustment of channel form in addition to discharge. The catchment study (based on three contrasting UK catchments) was undertaken to assess the usefulness of the residuals from the national model for assessing channel stability at a reach based on the evidence of adjustment throughout the river network. More specifically, the catchment study aimed to assess downstream changes in channel geometry to assess the extent to which change at the reach scale could be evaluated on the basis of upstream reaches and changing environmental conditions.

6.2 River channel stability

The residual values *were* found to be indicative of channel stability and the type of adjustment occurring within the channel. Under-wide channels (negative residuals) were associated with erosion which was severe in the case of some of the extreme residuals in class 1. In contrast, positive residuals, representing over-wide rivers in classes 4 and 5, were demonstrating deposition and few signs of erosion. A crude stability score based on ten indicators of adjustment (Sear et al., 1995) showed a clear relationship with residual magnitude demonstrating a tendency for rivers with negative residuals towards erosional processes and positive residuals towards no dominant process or signs of deposition. A scatter graph plotting residual values against stability score for each river confirmed the direction of the relationship but showed a weak R^2 value of 0.35. This leads to the conclusion that the magnitude of a residual value cannot directly predict the *degree* of stability for an individual river, but can represent the likely direction of change and possible severity of geomorphological processes supported by further investigation.

It was possible to identify particular types of behaviour in each class in relation to Downs' (1995b) classification of river channel adjustment. Class 3 contained rivers which demonstrated inactive and active stability, classified by Downs (1995b) as stable and lateral migration. In the case of inactive stability, little adjustment to bed and banks was observed. Active stability showed signs of channel migration with indicators of erosion and deposition linked with channel meanders but no overall change in the cross-sectional dimensions. The degrees of adjustment referred to by Downs (1995b) as the intensity of adjustment, were broadly indicated by residual magnitude, in particular with regard to erosion which was most severe in class 1.

The temporal study confirmed the findings from the field survey, with a tendency towards increases in width in class 1 rivers compared with decreases in width in class 5. In addition the hypothesis that rivers were moving towards the regression line was confirmed by the residual values calculated for the new Q_{maf} (based on the additional last ten years of flow data) in which 11 out of 16 rivers had shown a decrease in residual value. However, the temporal study also highlighted the differences between the amount and direction of change in each river and several important outcomes emerged. Rivers in class 3 were found to diverge from the regression line, indicating the transient nature of stability. It is impossible to tell from this research whether the degree of change is within the normal variability around a mean condition or to assess the time-scales of adjustment. However, it is clear that the residuals have changed over a ten year period highlighting the importance of predicting the likelihood of change when designing channel dimensions. The temporal study also demonstrated the importance of depth changes and the close relationship between depth and channel capacity. In some rivers, despite an increase in Q_{maf},decreases in width were compensated for by increases in mean depth and the relationship between width and depth is fundamental in understanding processes of channel adjustment. Often there is a tendency during empirical studies to address each element of channel cross-section as separate (Miller, 1991) but this research has shown that channel geometry studies must consider the mutual adjustment of channel parameters.

6.2 River channel characteristics according to residual value

It was found in the initial analysis of geometric and hydrometric data for the whole dataset (124 rivers) that residuals were representative of rivers of particular characteristics in terms of the magnitude of Qd, channel size and shape. Rivers where width was under-predicted in relation to discharge were on average wider than rivers where width was over predicted, that is over-wide rivers in relation to Qd tended to be wider in relation to under-wide rivers which had a lower mean width. However, this was not always the case and some of the rivers in class 5 had similar widths to rivers in classes 1 and 2 but remained over-wide in relation to Qd. The range of rivers in each class also showed considerable variability in rivers according to different geometric variables and Qd. Depth showed no relationship with residual magnitude although when combined with width to describe channel shape, the width:depth ratio did show a clear increase from class 1 to class 5 showing rivers in class 1 were on average deeper and narrower than rivers in classes 4 and 5. These apparent geomorphological groupings suggested that specific controlling factors may be the cause of deviation from the model line and were investigated further during the field survey.

6.3 The influence of dominant discharge

The difficulty of using a single channel forming discharge was discussed at length in Chapter 2 and is a fundamental problem with downstream hydraulic geometry models. It was clear that in some cases there were clusters of rivers in the extreme classes which deviate from the regression line because the channel dimensions are related to a flow regime other than the Q_{maf} equated with bankfull flow. This explanation was proposed for the chalk streams found in class 5 which are over-wide in relation to Qd but are narrower than other rivers with similar positive residual values contained within classes 4 and 5. These rivers are baseflow-dominated and are likely to be associated with bankfull discharges of much higher return periods than Q_{maf} (the Qd value used to predict bankfull width). Flow variability associated with the concept of memory in river channels (Pickup and Warner, 1979) may also be the cause of over-wide channels. Rivers which deviate from the regression line may be responding to flood events which occurred during the past. Some channels may still be responding to past climatic conditions. The extent of deviation may represent a difference in the channel forming discharge, the case with the chalk streams or alternatively the response of the channel to continuously fluctuating flow regimes. As previously stated, it is impossible to predict the time-scales of adjustment of under or over-wide rivers or whether the unstable behaviour observed at a reach is in fact part of the river network's response to the fluctuation discharge and sediment regimes.

Other local environmental factors were also investigated in terms of their control on channel form. The results from the geomorphological surveys of fifty river reaches selected from the national database showed that it was impossible to classify rivers with similar residual values according to specific controlling factors. It was found that different variables were found to influence rivers to varying degrees in each class and the influence of individual controlling factors could not be attributed to residual magnitude. However, several trends emerged from the results discussed below.

6.4 Bank materials

The positive residuals, over-wide in relation to Qd, showed two dominant types of river in terms of bank materials. Class 4 rivers are dominated by rivers with sand-gravel banks and it is suggested that the non-cohesive nature of the channel boundary allows over-widening of the channel during peak flow events. In contrast, 50% of rivers in class 5 are characterised by clay-silt bank materials associated with the chalk rivers in the south east of England. They are therefore more likely to be over-wide in relation to discharge as a result of the Qd used to predict channel width, as opposed to the influence of bank materials. This was confirmed when the residual values for rivers were plotted according to bank material type (clay-silt and silt-sand). There was found to be no significant difference at 95% confidence levels between channel geometry discharge relationships according to bank material types indicating that residual values cannot be differentiated exclusively on the basis of bank materials. Nevertheless, the fine nature of clay-silt sediments may contribute to the lack of channel adjustment observed in several of the rivers of this type. The majority of rivers in classes 1, 2 and 3 were in the clay-silt, silt-sand categories, representative of more cohesive channel banks. In comparison, class 4 rivers were dominated by sand-gravel banks, less cohesive and perhaps resulting in over-widening.

Bank materials were investigated in more detail during the catchment study where shear tests and particle size analysis were carried out to investigate bank strength related to river stability. The results showed, first, a difference between the degree to which percent silt clay and shear strength co-varied in each catchment and, second, a difference in the apparent influence of bank material characteristics on channel adjustment downstream.

The River Windrush contained relatively high percentages of fines (particle size < 0.063 microns) but this was not reflected in the shear strength of the banks which was much lower. In comparison, the River Livet showed a much closer relationship between the percentage fines and bank strength, indicating differences in the relative importance of factors affecting bank stability and the influence of secondary controls such as bank height, vegetation and other material properties. This was clearly demonstrated in the River Seven where bank strength increased sharply at Askew (site 4) despite a decrease in percentage fines, the change could be attributed to treelining and a significant increase in bank height perhaps as a result of incision.

Equally the relationship between changes in channel dimensions and bank material properties downstream varied in each catchment. The River Seven showed a strong inverse relationship between changes in bankfull width and shear strength downstream indicating that bank strength was an important control on width adjustment. The River Windrush showed some degree of association between channel width and percent fines downstream but this did not appear to be related to bank strength, which as previously suggested could be dependent upon other bank properties related to other material properties, for example, moisture content and electro-chemical properties associated with the clays. Finally, the River Livet differed from the other two catchments showing changes in width unrelated to relatively low and constant shear strength and percent silt-clay values downstream. In the River Livet however, bed material was found to have a close relationship with local channel gradient downstream and changes in channel capacity were concluded to be controlled by changes in channel depth downstream related to bed material size and gradient.

6.5 Bed materials

In the national study, the influence of bed materials on the residual values was more distinct than that of bank materials. Class 2, in particular, was dominated by bedrock channels and the narrow range of residuals in terms of width and discharge suggests that bed material is significant in causing a deviation from the regression line. It was interesting to find that where depth is less adjustable as a result of a bedrock control, channels were under-wide. This was in contrast to the expectation that where depth is constrained, channels may over-widen to allow adjustment to channel capacity. The River Seven supported the findings from class 2 rivers. Changes in the local channel gradient were closely related to changes in the long profile downstream and changes in maximum depth downstream were almost constant suggesting that changes to depth were limited. However, the river was under-wide and was demonstrating signs of bank erosion downstream.

In class 5 bed materials tended to be a mix of silt, sand and gravel associated with the channel banks which tended to be clay-silt. The River Windrush had a high positive residual value computed using the national regression model and was dominated by similar geomorphological characteristics to class 5 rivers.

Mixed bed materials dominated in class 3 and were representative of active stability downstream indicative of a balance between sediment supply and transport. Bed material size is closely related to gradient in the River Livet. The mutual adjustment of channel dimensions in response to external controls is apparent in the River Livet. This balance between controlling factors and channel adjustment is reflected in the low residual value of 0.83 derived from the national model, representing active stability.

6.6 Vegetation

The results from the vegetation survey in both the national and catchment survey showed that channel adjustment could not be directly related to vegetation. When the residual values from the national regression model were plotted according to vegetation type after Hey and Thorne (1986) there were no clear patterns and the type of vegetation showed no influence on residual magnitude. Further investigation of the role of treelining resulted in a complex picture; in some cases treelining appeared to increase bank stability preventing erosion; in other cases, it appeared to be associated with an existing erosion problem where channel width adjustment was prevented in places by tree root systems leaving unvegetated areas exposed to erosion.

The catchment study showed similar results with no clear cut influence on channel adjustment downstream in any of the catchment. However, it was possible to identify individual reaches where treelining could be a controlling factor. For example, Askew (site 4) on the River Seven showed an increase in bank stability which could be attributed to treelining on both sides of the channel. This highlights the importance of the geomorphological survey in assessing local factors at a reach.

The outcome of the discussion on local factors is that the residuals cannot be classified according to a single controlling factor. It is suggested instead that a combination of factors operating at each site expressed through the degree of stability at that site, is important in controlling channel geometry. Residual values can be used to indicate the degree of deviation from the model and likely direction of change which can then be used to suggest possible factors which might be operating to control river channel adjustment and can be further investigated during field survey.

6.6 Downstream adjustments and catchment scale controls

Graf (1982) argues that systematic variation in fluvial processes comes from two sources: first, external controls such as boundary conditions, vegetation and geology; and secondly, spatial variation imposed by structure, that is, the location of river reaches within the catchment in relation to sources of disruption. The catchment study highlighted the importance of investigating the adjustment of channel dimensions and gradient downstream in relation to drainage basin form or structure, often overlooked in channel geometry discharge studies. The morphology of the drainage basin was found to have a strong influence on channel morphology downstream. The control exerted on channel geometry at the catchment scale was examined in both longitudinal (valley slope) and lateral (valley bottom width) directions.

In the River Seven, valley slope and channel gradient were closely related. This was reflected in depth adjustments downstream where maximum depth remained almost constant from site S1 to site S5 suggesting a maximum level of incision. The constraint of channel depth adjustment and control on local bed slope imposed by valley slope results in the cross-sectional direction absorbing channel adjustment, evidenced in width adjustments in the River Seven and signs of erosion. The long profile in the River Windrush is almost flat reflected in low local gradients with little adjustment downstream. Valley slope and local gradient do not always co-vary, however, and the long profile does not appear to be exerting a strong control on local bed slope which is variable downstream, perhaps related to bed-level changes. In the River Livet, valley slope and channel gradient are associated in the lower reaches of the catchment but at site L2 channel gradient shows a significant decrease in bedslope related to increase in bed material size. Valley slope, in contrast with the River Seven, does not exert a dominant influence. Changes in gradient downstream are often discontinuous as a result of tributary confluences and the location of the reach within the catchment and the influence of network topology on channel geometry and morphological adjustment are important (Pizzuto, 1992).

In addition to establishing the importance of drainage basin form on channel form, the most important finding of the catchment study was the importance of understanding mutual adjustment of cross-sectional parameters and channel gradient, factors that are commonly considered in empirical work as separate elements of the system. The term mode of adjustment (referred to by Hey and Thorne (1986) as mode of operation) was used to describe the dominant mechanism by which cross-sectional form adjusts, either width, depth or slope adjustment.

The temporal study highlighted the importance of assessing downstream changes in width in relation to depth changes. As mentioned above, changes in depth were found to have a significant relationship with changes in channel capacity downstream (R = 0.72) over a ten-year period, suggesting that bed-level changes are important in controlling channel adjustment to changes in discharge of water and sediment and must be considered in relation to changes in width. The catchment study went on to show that different modes of adjustment were dominant in each catchment and the relationship between width and depth downstream must be viewed in terms of adjustment to channel depth and gradient.

7.0 APPLICATIONS AND RECOMMENDATIONS

Assessing river channel stability and sensitivity to change as a basis for river restoration and management

7.1 Use of the national regression model

- Development of any channel geometry - discharge relationships must adhere to the assumptions of regression analysis. The conclusions from the channel geometry - discharge relationship used in this research are only valid for the range of conditions represented by the dataset.
- On the basis of the research findings, the national regression model (124) relating bankfull width to Qd may be used to compute residual values for semi-natural river reaches in the UK where flow records are available (Chapter 4, sections). The residual value can then be used to give an indication of river channel stability and likely direction of change (see table 4.14, section). This information can be used to direct the geomorphological survey to further investigate channel stability and possible factors controlling channel adjustment.
- The exclusive use of downstream hydraulic geometry relationships for estimation of channel dimensions must be treated with caution. The results of the national model showed the degree of deviation about the model to be on average 3m within standard error bands of +/-1.0. In addition, variability within the model was geomorphologically significant indicating the importance of factors controlling river channel adjustment. Instead, the residual values should be used alongside the regression model to indicate variability and possible short term changes to be incorporated into design plans.
- At this stage, the regression model developed in this study *cannot* be used to assess stability in channelised river reaches based on the degree of deviation from the national regression line.

7.2 Desktop surveys

- On the basis of the research findings, desktop surveys for geomorphological assessment should incorporate a more detailed analysis of drainage basin form.

Measures of channel slope, valley width and morphometric data (Total Channel Length and Main Channel Length) should be taken at key sites throughout the catchment to be used in conjunction with data from geomorphologcial surveys and surveys of cross-sectional form.

- Data obtained during the desktop surveys in the catchment study were found to be related to adjustment of width and depth downstream and can be used to assess adjustment at a reach in the context of overall catchment controls. Morphometric measures provide a useful surrogate for discharge in terms of a preliminary assessment of the rate of increase in discharge downstream and the relationship of channel form to the drainage net.
- It is recommended that a more structured link be made between the desktop survey and field survey to relate changes in channel form (for example, channel width) to catchment scale controls (for example, valley bottom width) in addition to local scale environmental conditions.

7.3 Geomorphological Surveys

- The importance of geomorphological surveys (stream reconnaissance surveys) was confirmed during this research. Their use in obtaining detailed information on channel condition (degree of naturalness) and state (river channel stability) is imperative.
- Care should be taken when using terminology describing the condition of the river channel. The sensitivity index developed by Brookes and Long (1989) does not conform with geomorphological definitions of sensitivity and is more an index of naturalness or as more recently described by the Environment Agency in Guidance note 18 as 'Susceptibility to disturbance'. More clarification is required in this field.
- Indicators of adjustment are a useful and quick method of making an assessment of river channel stability at a reach and were found to be effective when combined with the results of channel adjustment both temporally (observed in the temporal study) and spatially (in the catchment study).
- Detailed geomorphological assessments (of the form shown in figures 5.4 and 5.7) should be undertaken at the key sites identified in the desktop survey incorporating as much geomorphological analysis as the scope of the project allows, for example, geotechnical surveys to assess bank stability.

- In addition, during the geomorphological survey, sites demonstrating particular geomorphological behaviour may be selected for more detailed investigation in the form of a fluvial audit (Environment Agency Guidance note 18). These should be supported by further map work to provide a catchment scale perspective.
- Classification of channel type from existing geomorphological data held in river databases (for example, RHS) is difficult and Rosgen's (1994) river classification developed for US streams, was not found to be useful in classifying UK river types. Rather than attempting to fit rivers to a national classification of rivers according to river type or geographical location, it is instead recommended that rivers should be viewed in terms of stability which is a function of local and catchment scale controlling factors.

7.4 Cross-sectional Surveys

- Cross-sectional surveys are recommended where possible to allow downstream changes in channel geometry and gradient to be plotted (for example, figure)and interpreted in relation to data from desktop and geomorphological surveys.
- By analysing the variability of mean depth, maximum depth, width and slope in relation to discharge downstream the dominant mode of adjustment can be identified. The findings from the stability survey in the catchment study clearly corresponded to observed channel adjustments downstream. There is a need for more quantitative assessment of channel adjustment throughout the catchment to support the geomorphological findings and provide a context for evaluation of the extent of channel change at a reach.
- The mutual adjustment of width and depth is important and should be taken into account when assessing the likely direction of change.
- Measures of width and depth can be used in different ways; to gain information of variability in channel geometry at a reach; to assess the extent of over or under-prediction by the national regression model; and to identify the average change in channel dimensions downstream.

7.5 Conclusion

A more structured geomorphological input to channel design is necessary to assess the degree of channel stability and sensitivity to change. There is clear evidence to show that adjustment at a reach can be assessed using residual values obtained using the national regression model (124 sites) to predict the likely direction of change supported by geomorphological surveys and more detailed measurement of channel geometry and slope downstream to identify the dominant mode of adjustment. A combination of geomorphological techniques should be used *based on the individual catchment and objectives of the project* to assess river channel stability. It is imperative that adjustments at the reach scale are linked to catchment scale changes in addition to local controls. On the basis of this type of investigation, a better understanding of likely channel adjustment over short time-scales can be gained and incorporated into design plans.

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APPENDIX 1

Site details for the dataset of 124 sites used in the regression model

ID no.	Station	River	Site name	Grid reference	Author
1	15001	Isla	Forter	NO 187 647	FSD
2	15002	Newton	Newton	NO 230 605	FSD
3	18001	Allan Water	Kinbuck	NN 792 053	FSD
4	18008	Leny	Craigie Hall	NT 585 096	FSD
5	19002	Almond	Almond Weir	NT 004 652	FSD
6	21003	Tweed	Peebles	NT 664 566	H&T
7	21005	Tweed	Lyne Ford	NT 206 397	H&T
8	21011	Yarrowater	Philliphaugh	NT 439 277	H&T
9	21012	Teviot	Hawick	NT 522 159	H&T
10	22002	Coquet	Bygate	NT 870 083	H&T
11	22003	Usway Burn	Shillmoor	NT 886 077	H&T
12	22007	Wansbeck	Mitford Flume	NZ 175 858	OD
13	22008	Alwin	Clennell	NT 925 063	OD
14	22009	Coquet	Rothbury	NU 067 016	OD
15	23005	NorthTyne	Tarset	NY 776 861	H&T
16	23008	Rede	Rede's Bridge	NV 868 832	H&T
17	23010	Tarset Burn	Greenhaugh	NY 789 879	OD
18	23011	Kielder Burn	Kielder	NY 645 947	H&T
19	24003	Wear	Stanhope	NY 984 391	FSD
20	24004	Bedburn Beck	Bedburn	NZ 118 322	FSD
21	24005	Browny	Burn Hall	NZ 259 237	FSD
22	24007	Browny	Lanchester	NZ 165 462	FSD
23	25006	Greta	Rutherford Bridge	NZ 034 122	FSD
24	25011	Langdon beck	Langdon	NY 852 309	OD
25	25012	Harwood Beck	Harwood	NY 849 309	OD
26	25019	Leven	Easby	NZ 585 087	OD
27	27012	Hebden Water	High Greenwood	SD 973 309	FSD
28	27032	Hebden Beck	Hebden	SE 025 643	FSD
29	27047	Snaizeholme Beck(1)	Low Houses	SD 832 883	H&T
30	27047	Snaizeholme Beck (2)	Low Houses	SD 832 884	H&T
31	27053	Nidd	Birtswith	SE 230 603	H&T
32	27055	Rye	Broadway foot	SE 570 855	H&T
33	27055	Rye	Broadway foot	SE 570 855	H&T
34	28020	Churnet	Rocester	SK 103 389	H&T
35	28038	Manifold	Hulme End	SK 106 595	H&T
36	28041	Hamps	Waterhouses	SK 082 502	H&T
37	28046	Dove	Izaack Newton	SK 146 509	H&T
38	28070	Burbage Brook	Burbage	SK 259 804	FSD
39	37016	Pant	Copford	TL 668 313	FSD
40	39015	Whitewater	Lodge Farm	SU 735 524	FSD
41	39025	Enborne	Brimpton	SU 568 648	FSD
42	39028	Dun	Hungerford	SU 321 685	FSD
43	40005	Beult	Stile Bridge	TQ 758 478	FSD
44	40007	Medway	Chafford	TQ 517 405	FSD
45	40012	Darent	Hawley	TQ 551 718	FSD
46	41015	Ems	Westborne	SU 755 074	FSD
47	41016	Cuckmere	Sheepwash Bridge	TQ 611 151	FSD
48	43005	Avon	Queens Falls, Amesbury	SU 151 414	FSD
49	43008	Wylye	South Newton	SU 086 343	OD
50	43012	Wylye	Norton Bavant	ST 909 428	H&T
51	44003	Asker	Bridport	SY 712 907	H&T
52	44004	Frome	Loudsmill	SY 708 903	H&T
53	45001	Exe	Thoverton	SS 936 016	H&T

ID no.	Station	River	Site name	Grid reference	Author
54	45002	Exe	Stoodleigh	SS 943 178	FSD
55	45005	Otter	Dotton	SY 087 885	H&T
56	45006	Quarme	Enterwell	SS 919 356	FSD
57	46002	Teign	Preston	SX 855 746	H&T
58	46003	Dart	Austins Bridge	SX 751 659	FSD
59	46005	East Dart	Bellever	SX 657 775	H&T
60	46006	Erme	Ermington	SX 642 532	H&T
61	46007	West Dart	Dunnabridge	SX 643 742	H&T
62	46806	Avon	Avon Intake	SX 681 641	FSD
63	47004	Lynher	Pillaton Mill	SX 368 624	FSD
64	47005	Ottery	Werrington Park	SX 336 866	FSD
65	47007	Yealm	Puslinch	SX 574 511	FSD
66	48902	Fowey	Restormel	SX 098 624	FSD
67	49001	Camel	Denby	SX 017 682	FSD
68	52005	Tone	Bishops Hull	ST 206 250	FSD
69	53008	Avon	Great Somerford	ST 966 832	FSD
70	53009	Wellow Brook	Wellow	ST 741 581	FSD
71	54014	Severn	Abermule	SO 165 958	OD
72	55010	Wye	Pant Mawr	SN 843 825	OD
73	55014	Lugg	Byton	SO 364 647	OD
74	55016	Ithon	Disserth	SO 024 578	OD
75	55017	Chwefru	Carreg y wen	SO 005 523	OD
76	55018	Frome	Yarkhill	SO 615 428	H&T
77	56004	Usk	Llandetty	SO 127 203	H&T
78	56013	Yscir	Pontaryscir	SO 003 304	H&T
79	58002	Neath	Resolven	SN 815 017	H&T
80	65001	Glaslyn	Beddgelert	SH 592 478	H&T
81	65001	Glaslyn	Beddgelert	SH 592 478	H&T
82	65002	Dwryd	Maentwrog	SH 670 415	OD
83	66002	Elwy	Pant yr onen	SJ 021 704	OD
84	67003	Brenig	Llyn Brenig Outflow	SH 974 539	OD
85	67005	Ceiriog	Brynkinalt weir	SJ 295373	OD
86	67006	Alwen	Druid	SJ 041 436	OD
87	67013	Hirnant	Rhiwaedog	SH 946 350	H&T
88	67018	Dyfrdwy	New Inn	SH 874 308	H&T
89	68004	Valley Wistaston Brook	Marshfield Bridge	SJ 673552	FSD
90	68005	Weaver	Audlem	SJ 652 432	OD
91	68007	Wincham Brook	Lostock Green	SJ 698 757	FSD
92	69034	Musbury Brook	Helmshore Intake	SD 773 212	FSD
93	70002	Douglas	Wanes Blade Bridge	SD 476 126	FSD
94	71003	Croasdale Beck	Croasdale Flume	SD 706 546	FSD
95	71005	Bottoms Beck	Bottoms Beck Flume	SD 745 565	FSD
96	71008	Hodder	Hodder Place	SD 704 399	H&T
97	71011	Ribble	Halton West	SD 850 552	OD
98	72003	Hindburn	Wray	ND 605 679	H&T
99	72003	Hindburn	Wray	ND 605 679	H&T
100	72804	Lune	Broadraine	SD 261 901	FSD
101	72807	Wenning	Hornby	SD 586 684	OD
102	73002	Crayke	Low Nibthwaite	SD 294 884	OD
103	73009	Sprint	Sprint Bridge	SD 515 961	H&T
104	73011	Mint	Mint Bridge	SD 524 944	H&T
105	74007	Esk	Cropplehow	SD 131 978	H&T
106	74007	Esk	Cropplehow	SD 131 979	H&T
107	75003	Derwent	Ouse Bridge	NY 198 321	OD
108	75007	Glendaramacken	Threlkeld	NY 323 248	H&T
109	76002	Eden	Warwick Bridge	NY 470 567	H&T
110	76004	Lowther	Eamont Bridge	NY 525 285	OD
111	76005	Eden	Temple Sowerby	NY 605 283	H&T
112	76008	Irthing	Greenholme	NY 486 581	H&T

ID no.	Station	River	Site name	Grid reference	Author
113	76009	Caldew	Holme Mill	NY 378 469	FSD
114	77001	Esk	Netherby	NY 390 718	FSD
115	78004	Kinnel	Redhall	NY 078 868	FSD
116	79002	Nith	Friars Carse	NX 923 851	FSD
117	79004	Scar	Capenoch	NX 845 940	FSD
118	79005	Cluden	Fiddlers Ford	NX 928 795	FSD
119	84009	Nethan	Kirkmuirhill	NS 809 428	FSD
120	84016	Luggie Water	Condorrat	NS 739 725	FSD
121	86002	Eachaig	Eckford	NS 140 843	FSD
122	*	Pinsley Brook	Cholstrey Mill	SO 462 598	H&T
123	*	Chitterne	Codford	ST 971 928	H&T
124	*	Ceidog	Llandrillo	SJ 035 372	H&T

Notes :

ID no. Identification number refers to the number of the site within the database of 124 sites
H&T Hey and Thorne (1986)
FSD Field Survey Data from Wharton (1989)
OD Overlap data classified by Wharton (1989) referring to sites which have both Field Survey data and Archive data
* No Institute of Hydrology gauging station number available

APPENDIX 2

Geometric and Hydrometric data for 124 sites used in the regression analysis

ID	Station	w	d	dmax	ESTCA	Qd	W:D	Standard Residuals
1	15001	16.5	0.89	0.74	12.5	46.93	18.51	-0.207
2	15002	4.3	0.49	0.40	1.7	7.43	8.78	-2.161
3	18001	16.4	1.42	1.15	19.04	69.46	11.57	-0.778
4	18008	29.4	1.35	1.04	30.58	82.02	21.78	0.977
5	19002	8.6	0.9	0.67	5.76	17.14	9.56	-0.986
6	21003	33.4	2.66	2.09	69.81	153.3	12.56	0.516
7	21005	31.2	2.22	1.47	45.86	91.3	14.05	1.027
8	21011	41.0	2.65	1.75	71.75	196	15.47	0.866
9	21012	31.3	2.83	2.13	66.67	126.8	11.06	0.566
10	22002	14.1	1.48	0.87	12.27	11.2	9.53	1.319
11	22003	9.1	1.11	0.78	7.10	17.6	8.20	-0.831
12	22007	27.0	1.03	0.74	16.95	98.45	26.21	0.423
13	22008	6.7	0.65	0.51	3.58	13.99	10.31	-1.550
14	22009	19.6	1.69	1.165	22.81	119.67	11.60	-0.955
15	23005	45.2	3.07	2.14	96.73	192.3	14.72	1.227
16	23008	32.2	1.96	1.44	46.37	95	16.43	1.078
17	23010	13.7	0.86	0.645	8.865	59.56	15.93	-1.180
18	23011	28.0	1.9	1.05	29.40	36.5	14.74	1.973
19	24003	22.7	1.03	0.74	16.95	121.92	22.06	-0.476
20	24004	12.6	0.88	0.59	7.59	25.39	14.28	-0.250
21	24005	13.8	0.92	0.76	10.28	37.56	14.98	-0.498
22	24007	7.9	0.99	0.76	6.03	13.86	8.00	-0.964
23	25006	16.5	1.24	0.98	16.09	72.77	13.30	-0.833
24	25011	8.4	0.96	0.825	7.02	17.93	8.75	-1.132
25	25012	14.5	0.86	0.655	9.53	36.67	16.86	-0.289
26	25019	6.1	0.64	0.54	3.28	6.11	9.45	-0.710
27	27012	12.3	0.8	0.62	7.63	13.49	15.38	0.584
28	27032	6.6	0.5	0.36	2.47	3.84	13.20	0.256
29	27047	15.6	0.96	0.51	7.96	7.5	16.25	2.242
30	27047	12.6	1.01	0.59	7.43	7.5	12.48	1.510
31	27053	31.8	2.79	1.92	61.06	170	11.40	0.199
32	27055	25.9	3.31	1.68	43.51	100	7.82	0.258
33	27055	23.0	3.05	1.9	43.70	100	7.54	-0.149
34	28020	14.4	2.76	1.96	28.22	34	5.22	-0.204
35	28038	17.0	2.1	1.12	19.04	28	8.10	0.644
36	28041	15.0	2.08	1.07	16.05	27	7.21	0.267
37	28046	13.7	0.77	0.5	6.85	7.1	17.79	1.876
38	28070	6.1	1.04	0.85	5.21	5.45	5.89	-0.501
39	37016	9.0	1.72	1.28	11.52	8.7	5.23	0.144
40	39015	6.1	0.49	0.4	2.44	1.08	12.45	1.808
41	39025	8.5	1.55	1.38	11.88	17.46	5.50	-1.045
42	39028	8.6	0.53	0.38	3.29	2.49	16.28	1.797
43	40005	16.3	2.49	1.93	31.46	38	6.55	0.061
44	40007	19.5	3.48	2.3	44.85	51.49	5.60	0.239
45	40012	11.3	1.63	1.18	13.33	5.97	6.93	1.465
46	41015	4.8	0.68	0.58	2.78	1.9	6.99	0.139
47	41016	5.4	1.54	1.13	6.11	9.74	3.51	-1.769
48	43005	18.8	1.73	1.37	25.8	12.31	10.87	2.170
49	43008	14.6	1.21	0.98	14.26	10.5	12.10	1.541
50	43012	9.6	1.2	0.82	7.87	7.1	8.00	0.657
51	44003	11.6	2.09	1.22	14.15	19	5.55	-0.109
52	44004	17.5	1.36	0.65	11.38	20	12.87	1.227
53	45001	42.7	2.45	1.46	62.34	154	17.43	1.351

ID	Station	Width	QDMAX	QDM	ESTCA	Qd	W/D ratio	Standard Residuals
54	45002	31.3	1.13	0.81	24.78	151.6	27.70	0.309
55	45005	25.2	2.41	1.58	39.82	104.0	10.46	0.108
56	45006	6.4	0.92	0.79	5.11	9.9	6.96	-1.211
57	46002	29.4	3.29	2.07	60.86	148.0	8.94	0.129
58	46003	25.2	1.68	1.03	25.96	229.53	15.00	-1.029
59	46005	12.8	1.5	1.07	13.70	17.0	8.53	0.388
60	46006	15.8	2.31	1.64	25.91	76.1	6.84	-1.043
61	46007	27.5	2.37	1.25	34.38	70.0	11.60	0.976
62	46806	11.0	1.11	0.71	7.84	26.39	9.94	-0.754
63	47004	11.7	1.08	0.76	8.85	43.49	10.79	-1.284
64	47005	17.6	1.28	1.13	19.96	46.87	13.71	0.013
65	47007	8.0	1.55	1.34	10.59	21.08	5.13	-1.553
66	48902	14.0	1.6	1.37	19.15	96.3	8.73	-1.804
67	49001	12.9	1.67	1.39	17.96	60.53	7.74	-1.404
68	52005	18.1	1.9	1.57	28.18	63.3	9.51	-0.319
69	53008	15.7	1.61	1.36	21.35	41.19	9.75	-0.183
70	53009	7.0	1.86	1.6	11.25	15.33	3.76	-1.532
71	54014	32.6	2.18	1.84	59.98	255.58	14.95	-0.301
72	55010	17.3	1.15	0.76	12.98	59.56	15.01	-0.387
73	55014	14.3	0.9	0.755	10.74	30.37	15.83	-0.077
74	55016	22.3	1.68	1.37	22.25	99.19	13.24	-0.251
75	55017	13.6	0.835	0.575	7.66	23.2	16.32	0.156
76	55018	10.2	2.34	1.75	17.85	22.0	4.36	-0.760
77	56004	48.5	3.98	2.59	125.62	304	12.19	0.811
78	56013	18.2	2.32	1.51	27.48	45.0	7.84	0.196
79	58002	28.7	2.94	2.33	66.87	172.0	9.76	-0.169
80	65001	25.2	1.47	1.06	26.71	53.0	17.14	1.076
81	65001	24.4	1.99	1.22	29.77	53.0	12.26	0.966
82	65002	25.2	1.4	1.14	25.2	142.06	18.00	-0.340
83	66002	15.8	1.41	1.205	19.045	80.53	11.21	-1.125
84	67003	10.3	1.16	0.88	9.02	11.83	8.88	0.165
85	67005	24.1	0.79	0.625	15.02	34.01	30.44	1.554
86	67006	17.8	1.47	1.06	18.84	82.01	12.11	-0.742
87	67013	18.4	1.4	1.14	20.98	50.0	13.14	0.082
88	67018	20.1	1.75	1.11	22.31	46.0	11.49	0.505
89	68004	5.8	1.33	0.94	5.46	10.87	4.35	-1.694
90	68005	8.2	1.82	1.325	10.815	23.79	4.48	-1.642
91	68007	11	1.72	0.99	10.89	28.04	6.40	-0.850
92	69034	3.7	0.91	0.73	2.66	4.87	4.01	-2.116
93	70002	14.5	1.8	1.37	19.865	28.59	8.06	0.069
94	71003	9.5	1.69	0.98	10.4	14.05	5.64	-0.349
95	71005	8.6	0.9	0.75	6.38	16.34	9.56	-0.918
96	71008	46.6	3.64	2.61	121.63	348.0	12.80	0.480
97	71011	26.9	2.015	1.78	47.825	117.5	13.35	0.156
98	72003	20.4	2.26	1.73	35.29	75	9.03	-0.147
99	72003	41.7	2.24	1.28	53.38	120.0	18.62	1.629
100	72804	36.0	1.51	0.99	35.49	243.26	23.84	0.110
101	72807	29.1	2.43	2.05	29.1	383.86	11.98	-1.275
102	73002	13.7	0.965	0.675	13.7	18.54	14.20	0.497
103	73009	17.5	1.81	1.29	22.58	50.0	9.67	-0.090
104	73011	19.3	2.39	1.62	31.27	74.7	8.08	-0.331
105	74007	22.9	1.99	1.26	28.85	61.0	11.51	0.546
106	74007	27.7	2.39	1.34	37.12	61.0	11.59	1.199
107	75003	36.1	1.9	1.19	42.96	93.03	19.00	1.500
108	75007	18.6	2.14	1.22	22.69	45.0	8.69	0.271
109	76002	57.8	4.06	2.69	155.48	424.0	14.24	0.934
110	76004	24.4	0.88	0.66	16.1	123.25	27.73	-0.247
111	76005	57.8	4.06	2.69	155.48	237.0	14.24	1.770
112	76008	32.2	2.05	1.34	43.15	60.4	15.71	1.729

	Station	Width	QDMAX	QDM	ESTCA	Qd	W/D ratio	Standard Residual
113	76009	18.1	0.90	0.63	11.47	87.48	20.08	-0.784
114	77001	54.8	1.55	1.14	62.47	736.08	35.35	-0.041
115	78004	17.0	1.85	1.44	25.29	72.18	9.19	-0.717
116	79002	43.0	1.28	1.03	44.29	487.90	33.59	-0.281
117	79004	23.9	1.56	1.02	24.15	148.76	15.32	-0.588
118	79005	21.5	1.68	1.42	30.62	128.26	12.80	-0.738
119	84009	15.5	2.02	1.72	26.61	41.59	7.66	-0.248
120	84016	8.9	1.36	1.13	10.15	23.25	6.51	-1.326
121	86002	24.2	1.60	1.26	30.60	79.91	15.09	0.341
122	*	10.6	1.39	0.82	8.69	14.00	7.63	0.021
123	*	6.5	1.17	0.68	4.42	3.90	5.56	0.181
124	*	13.0	1.86	1.23	16.00	48.00	6.99	-1.050

Notes:

ID no.	Identification number refers to the number of the site within the database of 124 sites
Station	Refers to the reference number of the gauging station used by the Institute of Hydrology
w	Bankfull width
d	Mean bankfull depth
dmax	Maximum depth
ESCTA	Estimated channel capacity (calculated by multiplying w and d)
Qd	Dominant discharge
W:D	Width:depth ratio

APPENDIX 3

Geomorphological survey sheets used in the national study (Chapter 4)

SECTION 1 SITE DETAILS

River	
Site	
Gauging Station	
Grid reference	
Previous research	
Site no.	

Date	
Time of Survey	
Present	

Qualitative Description

SECTION 2 NATURALNESS CHECKLIST

1) FULLY CHANNELISED

Culvert		loss of bank veg	
Concrete		loss of plant life	
Realigned		Artificial structures	
Resectioned		Trapezoidal channel	
Regraded		Recent engineering	
Alteration of flow		Ancient engineering	

2) BOTH BED AND BANKS SIGNIFICANTLY ALTERED

3) ONE BED OR BANK ONLY ALTERED

BED

Loss of riffle pool sequence	
Dredging	
Artificial structures	
Point bars	
Sand banks	

BANKS

	LH	RH
Rip Rap		
Armourment		
Artificial structures		
No Alteration		

4) OLD ENGINEERING WORKS WITH SUBSEQUENT READJUSTMENT

DETAILS OF READJUSTMENT

Regraded	
Trapezoidal	
Redev. of pool/riffle	
Braided	
Meandering	
Flow regime	
Point bars / sand bars	

BANKS

LH		RH
	Walled	
	Supported	
	Armoured	
	Regrowth of veg	
	Moss	
	Algae	

5) INSTREAM DEVICES/ENHANCEMENT

Berms	
Deflectors	
Weirs	
Others	

6) NO STRUCTURAL ALTERATION

Weed cutting	
Snagging and Clearing	
Dredging >15 yrs	
>5	
<5	

7) NO HUMAN INFLUENCE

No evidence of man-made structures	
Pool-riffle sequences	
Natural vegetation	
Bank vegetation	
Point bars	
Natural flow features	

SECTION 3 STABILITY CHECKLIST

INCISION	y/n	Details
Terraces		
Old Channels		
Undermined Structures		
Narrow Deep Channel		
Bank Failures		

AGGRADATION	y/n	Details
Buried Structures		
Buried soil in banks		
Large uncompacted bars		
Deep fine sediment overlying gravel		
Many unvegetated shoals		

SECTION 4 CHANNEL CHARACTERISTICS

BANK MATERIALS	LH	RH
Clay		
Silt		
Silt/Clay		
Sand		
Sand/silt		
Gravel		
Sand/gravel		
Cobbles		
Boulders		
Artificial		

BANK STABILITY

	LH	RH
Cohesive		
Non-cohesive		
Eroding		
Slumping		
Tree-lined		
Vegetation		
Bedrock		
Artificial		
Protection		

BANK PROFILE

	LH	RH
Asymmetrical		
Symmetrical		
Cliff		
Berm		
Artificial		

SUBSTRATE CHARACTER

BED SEDIMENT TYPE	
Clay	
Silt	
Sand	
Gravel	
Cobbles	
Boulders	
Bedrock	
Artificial	
BAR FORMS	
Pools/riffles	
Alternate bars	
Mid-channel bars	
Point bars	
Tributary Junction bars	
Vegetation Stabilising bars	

LANDUSE

Description	**LH**	**RH**	**Upstream**
Cultivated			
Pasture			
Urbanised			
Partly built up			
Riparian buffer strip			
Road development			
Reservoir			
Other			