UNIVERSITY OF SOUTHAMPTON

METHODS OF HISTORICAL RIVER CHANNEL CHANGE RECONSTRUCTION AND THEIR APPLICATION TO APPLIED GEOMORPHOLOGICAL RESEARCH

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ABSTRACT

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METHODS OF HISTORICAL RIVER CHANNEL CHANGE RECONSTRUCTION AND THEIR APPLICATION TO APPLIED GEOMORPHOLOGICAL RESEARCH

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Documented historical records have provided an invaluable source of information for allowing the geomorphologist to reconstruct the historical sequence of change. However, the application of historical reconstruction techniques for aiding geomorphologically sensitive river channel management has hitherto not been exhaustively studied. The precision with which historical change may be extrapolated is dependent on the ability of the geomorphological investigator closely to match the scale of river channel adjustment to the resolution and accuracy of the historical records. Historical reconstruction of river channel change is limited, therefore, by the inherent nature of the historical sources and the operational procedures used to interpolate river channel change information.

This thesis examines the geomorphological significance of scale in space and time to provide a conceptual basis for understanding river channel change. This allows the investigator to evaluate the demands required in seeking answers to river channel change questions that are appropriate to the nature of the geomorphological enquiry. To achieve these requirements, the thesis considers the nature and magnitude of errors associated with a range of historical sources of information. Methodologies are presented which demonstrate how planform, cross-sectional and ground-based historical photographic information may be used to extrapolate river channel change for three morphologically different river channels in England and Wales (the rivers Towy, Sence and Tillingbourne respectively). For each methodology the inherent limitations of the historical source information and operational errors associated with each methodology are considered. The type of historical information is demonstrated to be appropriate to the nature of the channel adjustment in order to yield valuable information to aid the interpolation of patterns of past channel behaviour.

The contribution of historical geomorphological techniques to aid river channel management is considered. The example of the River Wey is used to demonstrate how a suite of historical sources of information may be used in conjunction with contemporary field observations to address specific river channel management challenges. A GIS-based method of compiling and manipulating multi-type historical information is demonstrated an effective aid to the interpolation of river channel change. Historical information is demonstrated to be effective in providing a historical context for understanding contemporary patterns of river channel behaviour and developing appropriate recommendations for management. The successful application of applied geomorphological expertise is demonstrated to be as much a reward of effective communication as geomorphological interpolation.

The wider implications for the research is considered through the considerations of the practical challenges for the effective integration of historical geomorphology with river channel management and proposes a series of recommendations based on the findings of this research.

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CHAPTER 1

INTRODUCTION

1.1 RIVER CHANNEL HISTORY

The contemporary river landscape is considered one that has been shaped and modified by historical events, the diversity of contemporary characteristics reflecting wide spatial and temporal diversity of controlling stimuli attributed to physical and human actions.

Historical events occur with varying magnitude and with varying frequencies. Different events or combinations of events will provoke different responses in the river system at different spatial and temporal scales. The ability to attribute historical events to historical change provides a conceptual basis for understanding a river channel's contemporary stability and sensitivity to adjustment with which to predict future adjustments. Geomorphological science has made great progress in providing solutions towards answering questions concerning where, when and why river channel change may occur, but definitive answers are seldom possible.

Geomorphological events may act simultaneously, may be dependent on one another and may exert direct and/or indirect effects upon the river system. Furthermore, these events may effect the whole or merely part of the river system and there is no guarantee that the same process or combination of process for the same reach of the same river will necessarily result in the same outcome as different reaches and different rivers exhibit different sensitivity to adjustment. Events may be abrupt and potentially catastrophic in promoting sudden, possibly unpredictable change in the river system partially obscuring or totally over-writing previous channel characteristics. Progressive environmental change may cause sudden changes, or may cause the river channel to change steadily with poorly defined boundaries. As such, both events and responses may be termed 'pulsed' or 'ramped' (Brunsden and Thornes, 1979) dependant on the resolution at which they are observed. The 'geomorphological effectiveness' (Wolman and Gerson, 1978) of events to promote change may also be considered scale dependant. If a sufficiently long (typically geological) history of river channel evolution is considered then the perception of random occurrence that may accompany the 'catastrophic' event may be rationalised to a probability of reoccurrence.

While history has shaped and modified past river channel change this does that necessarily mean that river channel behaviour will necessarily follow a similar trend in the future. Schumm (1991) notes that the century held notion of uniformity ("The present is the key to the past") and actualism ("explanation, post-diction and prediction are based on the understanding of present processes") may either be lauded as a basic principle of geology or as a worthless concept. Human activity has typically over-written physical mechanisms as a means of promoting direct and indirect channel adjustment. The thesis must therefore address the question as to 'how' relevant is the past in determining the future?

Interpreting river channel history is multi-faceted. For most, the perception and understanding of the characteristics of any given river are best summed up in terms which are closely dependant on human association with the river. This perception is itself time dependant and rivers will assume different social, cultural and economic significance dependant on time and place. This relationship can be traced back centuries; for example, the Domesday Survey of 1086 recorded over 5000 mills (Purseglove, 1988), post 16th Century water management in England established an era of modernism and technical innovation (water pumps, locks and sluices). As such, the notion of what might be considered a 'natural' river may be highly subjective (Cosgrove, 1990). 20th Century technological development has seen even greater dis-association between humans and rivers. Nowhere is this more evident than in our cities where rivers may have been reduced to little more than culverts and concrete and steel lined drainage channels. It is quite possible that common knowledge and understanding of rivers is more out of touch with reality than at any other point in history.

The geomorphologist stands at a unique vantage point to provide an insight into channel history. If geomorphology can be used successfully to extrapolate and interpret past river channel changes then it may provide a unique standpoint from which to distinguish contemporary form and process, and provide a basis for making future predictions of river channel change.

The geomorphologist has a range of techniques available to extrapolate river channel history. Historical river channel change studies in geomorphology are now well accepted as one such technique (e.g. Hooke and Kain, 1982). 'Traditional' approaches using maps and airborne imagery are now well established as a means to providing a range of indices and have been used in many branches of geomorphological research with more recent technological developments providing increased scope for optimising the available historical evidence. However, despite advances made in academic research, the utility of these approaches in aiding applied geomorphological research has hitherto not been exhaustively examined and implemented.

River channel history history may be considered valuable to river channel management for two principle reasons:

a) It provides a means of understanding a river channel's evolution and the ability to reconstruct past changes. This allows the investigator to attempt to identify channel forming events and provide a contemporary context for the determination of contemporary river channel stability and future adjustment.

b) It provides an analogue of the past as a means of providing a point of reference for placing contemporary river channel characteristics and changes in historical context.

The thesis investigates examples selected from England and Wales as these rivers fall within the remit of the Environment Agency (formerly the National Rivers Authority) as this thesis is supported by a CASE studentship with the former Authority. However, while the methods illustrated draw from historical sources of information in England and Wales the theoretical background which underpins their application has universal relevance.

1.2 THE OBJECTIVES OF THIS THESIS

The aim of this thesis is to present a range of methodologies for extrapolating river channel change from historical sources of information and to investigate the value of these methods for aiding geomorphologically sensitive river channel management.

Fundamental to this understanding is for the investigator to understand the relevance of the results of the historical enquiry in geomorphological terms and the ability to apply this information in a manner to answer specific river channel change questions. An important step in this direction is an appreciation of the limitations of the historical information to achieve these objectives; the resolution of the information in space and time to represent change at varying scales and the accuracy of this information reliably reconstruct change. Of note in this respect is the ability of traditional methods of historical analysis reliably to represent historical river channel change as the size of the river channel and displacement of features decreases. For a given scale of river channel representation there comes a point when the historical information is no longer able to discern subtle change and it is impossible to distinguish river channel changes which may be considered 'real' above the noise of combined individual component errors which become increasingly apparent as the limiting resolution of the information is approached. Many river channels in England and Wales have been assumed to be historically stable on the basis that the analysis of traditional historical sources of information have been unable to reliably distinguish river channel change. However, field-based observation may clearly demonstrate that smaller river channels may be exhibiting patterns of change which may have direct significance to river channel management.

The objectives of this thesis may be summarised as follows:

a) To investigate river channel history through an understanding of space, time, and scale and resolution.

b) To investigate the limitations of historical information to extrapolate historical river channel change by considering the propagation of errors and the significance of error to the determination of change.

c) Description of three methodologies using historical information with varying resolution and accuracy to extrapolate historical river channel changes for a variety of river channel environments in England and Wales.

d) Consider the contribution of this information to aiding geomorphologically sensitive river channel management.

1.3 STRUCTURE OF THE THESIS

This section provides a breakdown of the structure of this thesis to fulfil the aims and objectives outlined in the previous section.

Chapter 2 provides a review that considers the nature of river channel change and of the contribution that river channel change studies may make towards geomorphologically sensitive river channel management. Firstly, the review may be considered in three sections. Secondly, the notion of river channel history and how an understanding of scale may determine the investigators perception of a rivers evolution. Finally, the chapter reviews the role of historical information sources to aid geomorphological reconstructions of river channel change in England and Wales.

Chapter 3 considers the accuracy of historical information. The chapter makes the assumption that if it is possible to understand the propagation of errors, from the moment when the river channel change information was recorded to the product of the historical analysis, then it should, in theory, be possible to attach confidence to the river channel change results. As such, this information will allow the investigator to select historical information that is appropriate to the river channel change questions asked and the ability to distinguish patterns of true adjustment above the noise of combined component errors. The chapter defines the nature of component errors through an understanding of their transcription of component inherent and operational errors.

Chapters 4, 5 and 6 describe three methodologies for extrapolating river channel change from historical information at varying levels of spatial and temporal resolution. Although the three methodologies differ they share common characteristics which are illustrated in each chapter: firstly, in each example, the method of historical analysis is addressing a specific scale dependant challenge. As such the methods may be deemed appropriate to a range of river channel environments in England and Wales. Secondly, the errors associated with each method are considered and, where possible, are used to estimate the magnitude and the significance of Total Error. Finally, the application of each of these techniques to aiding geomorphologically sensitive river channel management is considered.

Chapter 4 considers a Geographic Information Systems (GIS)–based approach to extrapolating river channel planform change on the River Towy, Dyfed. The method uses sequences of historical maps and aerial photographs dating from 1839 to reconstruct river channel planform changes for three study sites selected in the lower Towy valley. The River Towy was chosen specifically for this study because extensively published research has already clearly demonstrated the nature and magnitude of planform adjustment since the 19th Century. The GIS-based approach describes three methods for estimating change based on the digital representation of the river channel boundary. Furthermore, the method allows the investigator to estimate the magnitude of inherent and operational errors to determine an estimate of Total Probable Maximum Error based on a 'worse case' extreme for a given information format, scale of representation, river channel dimension and scale of adjustment. This information allows the investigator to make an informed judgement in order to distinguish true changes from the inherent noise of accumulated errors.

Chapter 5 considers an approach for extrapolating river channel change from cross-sectional information based on historical cross-sectional information obtained for the River Sence, Leicestershire. A re-survey of the River Sence in 1993 relocated the documented cross-sectional locations. The information is analysed to consider in situ change at individual cross-section locations over the 28 years of study and describes a GIS-based method by which information representing river channel changes at individual cross-section may be analysed spatially. The chapter describes the limitations of cross-sectional information for representing river channel changes and considers the transcription of errors for limiting the methodology's ability to be used effectively for other river channels.

Chapter 6 describes a qualitative approach for extrapolating river channel change information from the comparison of geomorpholgical information obtained from contemporary field evidence with historical ground-based photographs. More traditional approaches using maps, aerial photographs and cross-section information are unable to distinguish river channel change. The example chooses the River Tillingbourne in Surrey, a rural river channel which, by nature of its physical size and minimal planform adjustment would not yield channel change were more traditional sources of information used. The spatial resolution of these sources of information would be too poor to delimit river channel features of interest and extended reaches of the channel are covered with vegetation making the river channel impossible to observe consistently from aerial photography. Comparison between ground-based photographs taken at selected sites on the River Tillingbourne in 1935 with contemporary field evidence provides sufficient information for the investigator to reconstruct a much clearer expression of river channel change and contemporary stability than would otherwise be obtained. Additional investigation of the supporting historical information allows the investigator to reconstruct a long and detailed history (albeit qualitative) of river channel change dating back nearly 1000 years. This chapter serves to illustrate that the perception of lowland river channel stability is somewhat simplistic and that the history of human intervention may be considered for longer periods, up to 200 years typically associated with planform evidence.

Chapter 7 considers the application of historical research to aid geomorphologically sensitive river channel management. The chapter starts by considering the contemporary role of geomorphology in river channel management in England and Wales and the challenges for geomorphological research to embrace geomorphological principles. An example of a geomorphologically directed investigation is presented, conducted on behalf of the Environment Agency. The example considers the case of the River Wey (Environment Agency, Thames Region) and investigates the problems faced by river channel managers in determining the causes of sedimentation, problems associated with the River Wey and Godalming navigation and making geomorphologically sensitive management recommendations. The study is able effectively to demonstrate the value of historical information in supporting the field-based analysis. In particular, further to the remit of the original investigation, the thesis considers the value of a Geographic Information Systems (GIS)–based database constructed as a means of storing and representing a suite of historical and contemporary information allowing the investigator to establish spatio-temporal relationships in the information to optimise the diverse nature of this information.

The final Chapter, 8 returns to the series of river channel change questions asked in Chapter 2 and considers the extent to which the research illustrated in this thesis may aid the geomorphologist in providing answers. The chapter considers the challenges remaining and raises questions that have been borne out of this thesis for consideration in further research. Finally, an overview of current ongoing research is outlined.

CHAPTER 2

REVIEW

2.1 INTRODUCTION

The aim of this chapter is to review a range of background literature in order to provide a context to support the arguments and proposals outlined in this thesis. Specifically, the chapter will outline the value of historical approaches in geomorphology as an aid to identifying and characterising river channel change. This information may then be used to examine how historical approaches may better promote an understanding of river channel change. This chapter will meet these aims through the following objectives:

a) River channel history: Consideration of the nature of river channel change and of river channel history, to investigate exactly what components of the river channel may change and over what time scale. Fundamental to this is a review of geomorphological scale, space, time, and the concept of geomorphological stability.

b) Extrapolation of river channel history: This will involve a review of the extrapolation of historical geomorphological information in general and a specific investigation into methods used in the interpretation of historical sources of information.

2.2 HISTORICAL PERSPECTIVES AND SCALES OF APPROACH

2.2.1 Geomorphological questions

Gregory (1987) provides a useful approach that will be adopted for reviewing a contemporary understanding of river channel change by asking a series of river channel change questions (Figure 2.1). Each of these questions requires progressively greater understanding of river channel behaviour and as such the confidence with which future river channel changes may be predicted decreases with each successive question. The questions provide a useful basis to understanding river channel change because the ability to answer these questions is determined by the definition and distinction of theoretical geomorphological thought that underpins the answers. The aim of this section is, therefore, to review the nature of river channel change in conceptual terms as a basis for answering Gregory's questions and provide a context for providing answers. This will be achieved through consideration of the following concepts:

a) An investigation of the 'scale' of river channel change in order to develop an appreciation of the importance of scale and resolution to geomorphological history.

b) The measurement of river channel change through an understanding of the concepts of space and time.

c) An investigation of the relationship between space and time as a basis for understanding landscape evolution, thresholds of adjustment and river channel stability.

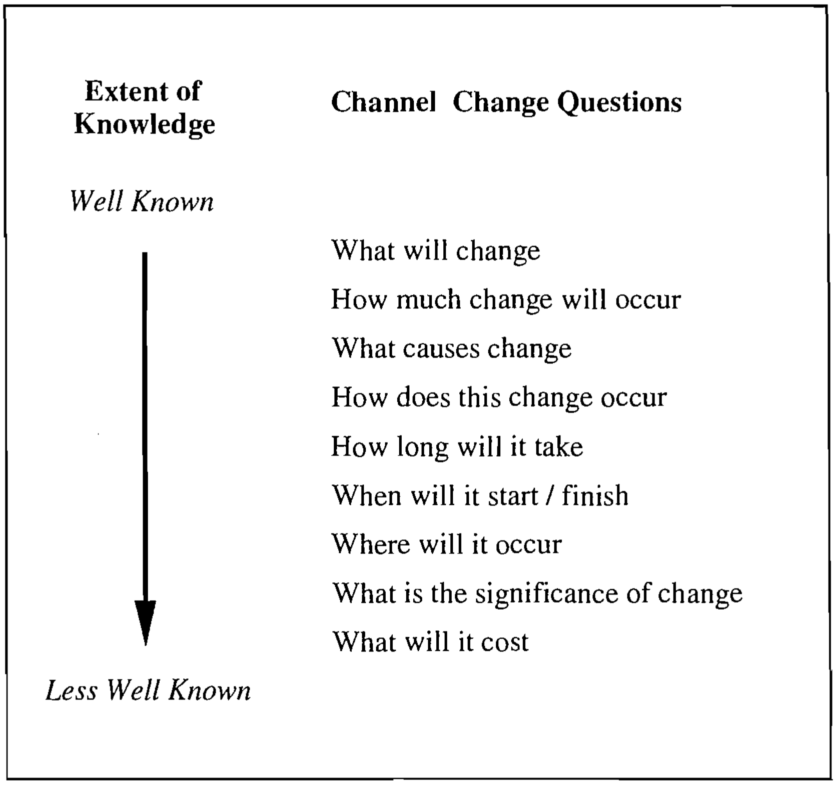


Figure 2.1 Channel change questions (Gregory, 1987)

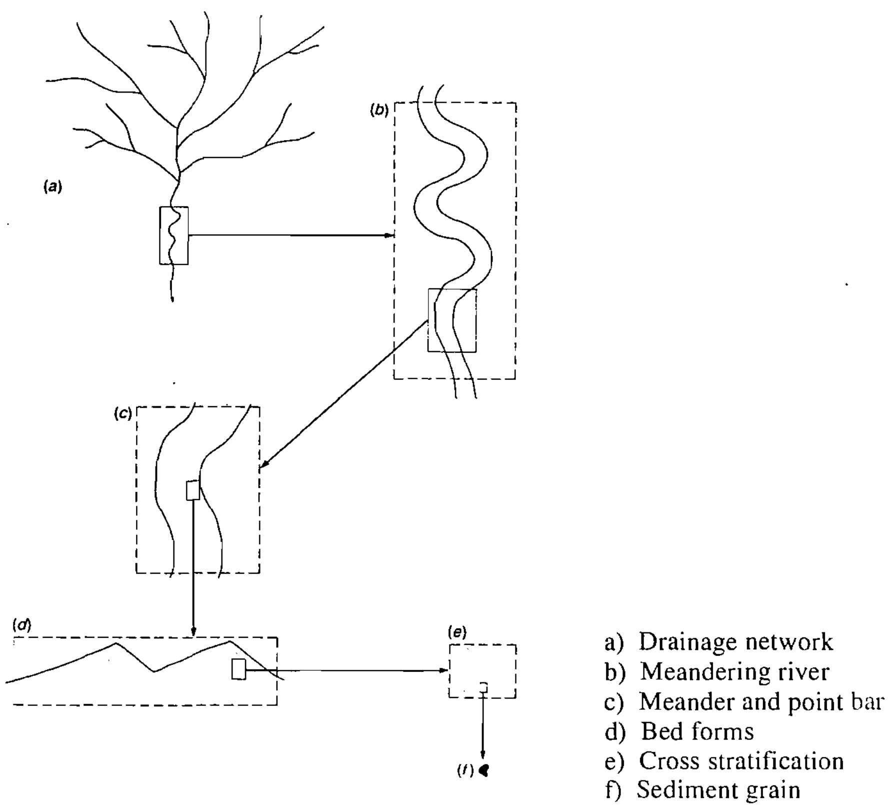


Figure 2.2 Components of the fluvial system (Schumm, 1991)

2.2.2 Scale

The notion of scale has long formed a central element in geomorphological debate and the recognition of scales of adjustment is crucial if geomorphologists are to establish an understanding of river channel change and the determination of river channel stability. Scale describes the dimension in space and time over which physical phenomenon exist. Resolution refers to the dimension in space and time over which physical phenomenon may be extrapolated. Therefore, it is important that the geomorphological resolution adopted for a given channel change investigation is appropriate to the scale at which the changes occur.

Geomorphologists have considered river channels at a considerable range of spatial and temporal scales. Typically the terms 'macro', 'meso' and 'micro'- scales have been used subjectively to illustrate such arguments, if time and space are considered independent of each other (Schumm, 1985).

In Space

River channel phenomenon exist at a range of spatial scales. Figure 2.2 illustrates that at the micro-scale fluvial enquiry might consider an individual sediment particle; at meso-scale levels the investigator might consider individual sections and reaches of the river channel, at macro-scale levels the entire river basin and drainage network. At each level geomorphologists have sought an appropriate resolution at which to observe features in space. For example, Terwindt and Kroon (1993) note with respect to the coastal environment (although their statement holds true for the fluvial environment too) that, "The selection of the scale of interest in a certain coastal problem is arbitrary. However, once selected, this scale establishes the scale of the morphodynamic entities" (p.194).

Also important is the consideration of the inter-relationship between scales. Engineering-based approaches in the past may be accused of being too scale specific in their approach, typically focusing at the small scale without due consideration of others. Jiongxin (1991), for example, observes that bedding patterns (micro-scales) have close association to planform characteristics (meso-scales) and proposes an inherent unity between these spatial scales. As such, Jiongxin argues that, in theory, an understanding of past forms at one spatial scale will allow inference and analogy at other scales.

Spatial 'resolution' refers to the scale at which we observe and extrapolate information from the landscape. The 'complexity' of the river channel will increase in proportion to the mismatch between spatial scale and spatial resolution, and the 'size' of the feature.

An example may be illustrated in Figure 2.3. Here, an investigation into drainage basin network pattern (macro-scale) observed at low resolution would generalise physical features and yield a low complexity impression of the drainage network. If the spatial resolution is increased, so the amount of spatial information pertaining to the drainage network increases. This will yield a high complexity impression of the drainage network. Fixing the spatial scale and resolution but increasing the size of the feature will have a similar effect. For example, large drainage basins are

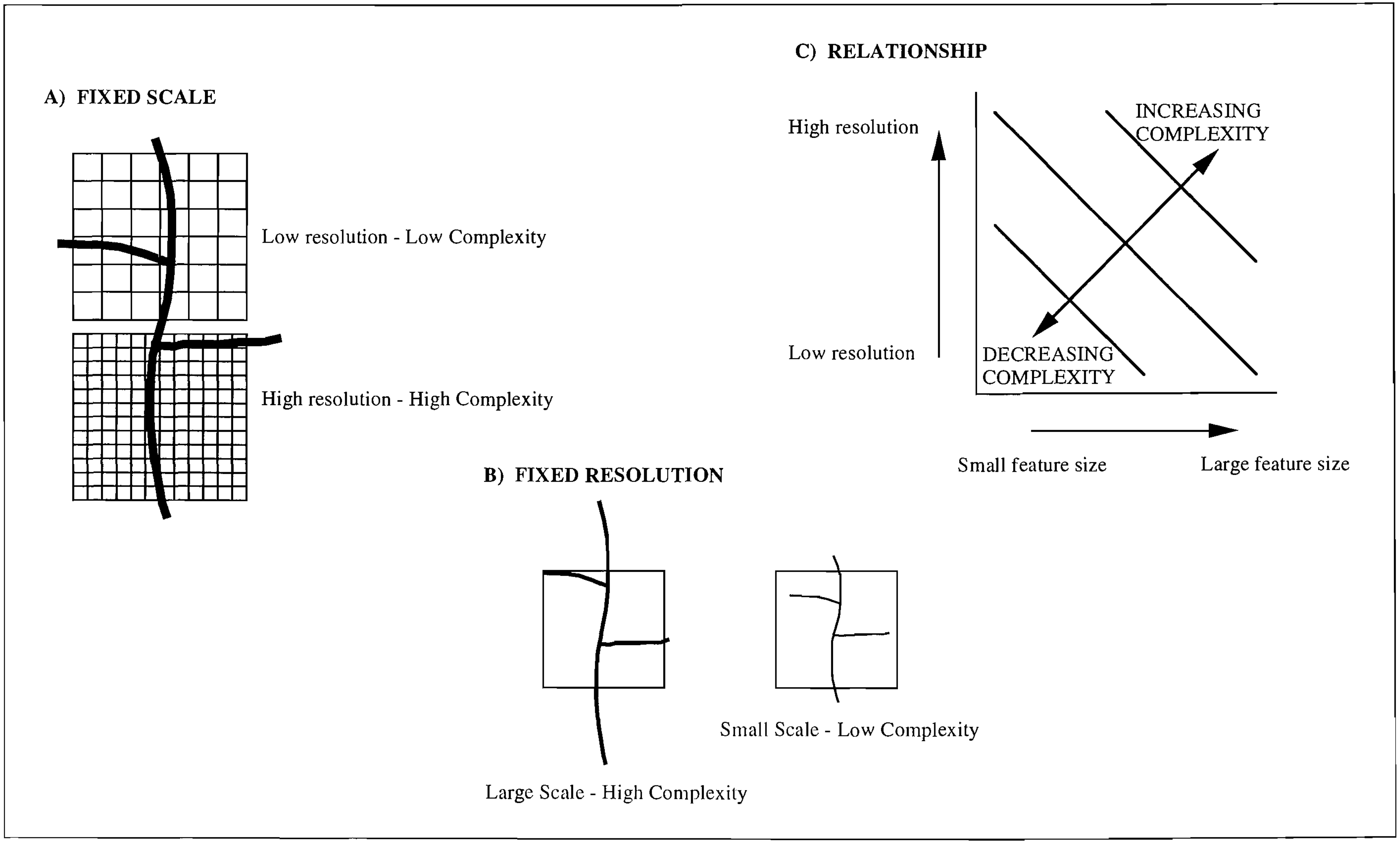


Figure 2.3 The relationship between scale, resolution and river channel complexity
A) Fixed spatial scale - variable spatial resolution B) Fixed spatial resolution - variable spatial scale C) Relationship.

typically more geomorphologically complex than small drainage basins. Reversing the arguement then, the size of a feature may be considered to be a function of spatial scale and resolution.

To illustrate this argument consider the example provided by Harvey (1984) of the intermittent semi-arid Rambla Honda in Almeria, Spain. Storm localisation within the catchment may mean that certain parts of the system will respond geomorphologically to runoff while others will not. River channel change is therefore spatially delimited as a function of the catchment's size. Similar spatial dependency occurs with geology, land-use etc. Conditions that may be considered independent at larger spatial scales can be considered dependent at smaller spatial scales where controlling variables may be considered homogenous. Furthermore, the ability of the geomorphologist to extrapolate and interpret river channel response is dependent upon the choice of spatial resolution with which the river channel is observed. A further example is provided by Wilby (1996) who considers space in terms of the 'fractal index' (Figure 2.4). Wilby demonstrates that the length of a river channel (in this example the River Soar, Leicestershire) is proportional to the resolution at which it is observed. Increasing the resolution of observation provides a different perception of overall channel length. It is important to stress that the spatial resolution of the geomorphological investigation should be appropriate to the questions being asked. Choosing a spatial resolution above or below that which is optimal to the study may result in loss of efficiency as information redundancy or generalisation occur respectively.

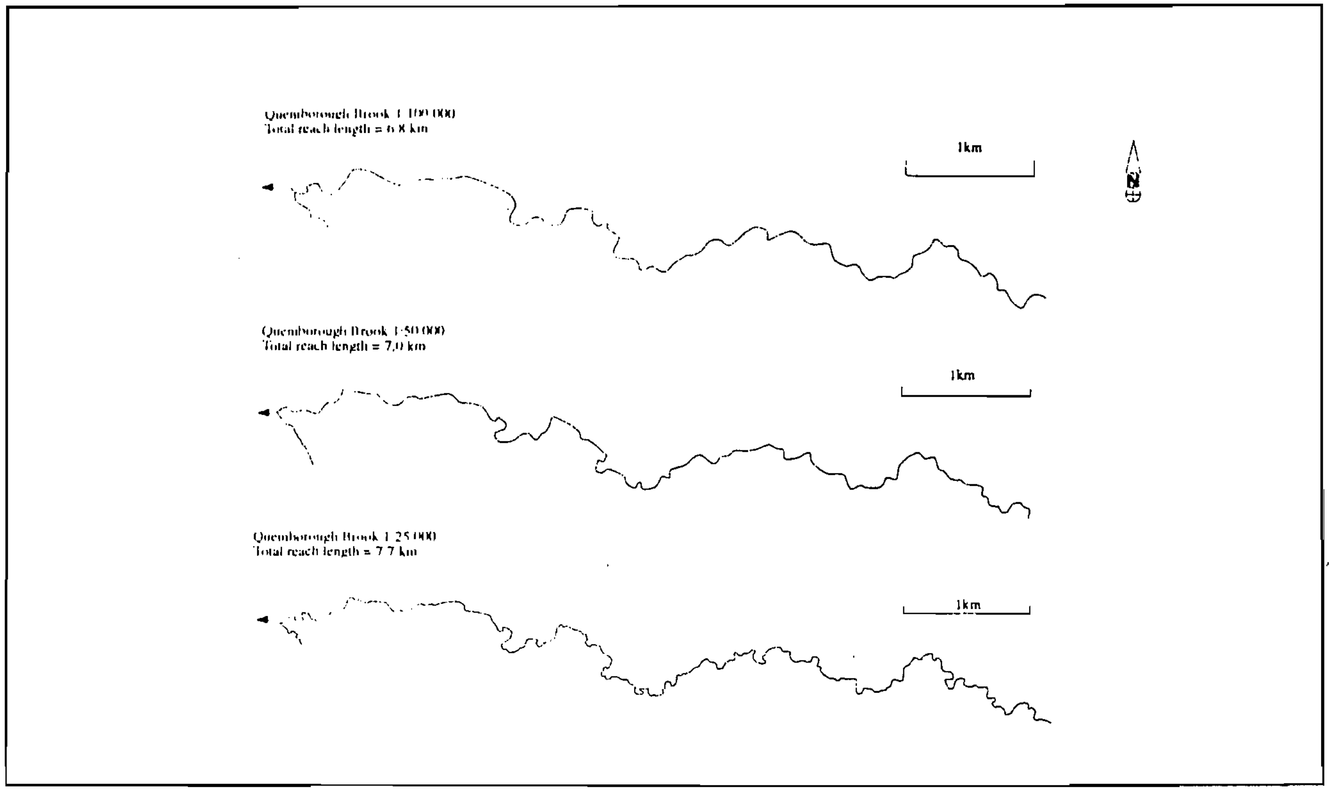


Figure 2.4 Fractal properties of the Queniborough Brook, Leicestershire (Wilby, 1996)
The total channel length increases as more detail is included with increasing map resolution.

In Time

Temporal scales refer to the 'period' over which phenomenon exist. As with space, time scale may similarly be defined at micro to macro scales, but these terms are somewhat abstract if conceptualised outside of the time scale of human life and experience. Schumm and Lichty's (1965) paper provided a milestone in the understanding of geomorphological time and the relationship to landscape development. In particular, it drew attention to the two previous notions of time and landscape development, that of the Davisian notion of 'cyclic' time and 'graded' time (Mackin, 1948). Cyclic time scales were considered periods over which the independent physical controls of geology, relief and climate would dominate patterns of landscape evolution. All other controls (e.g. vegetation) were considered to be dependant on these primary controls at this temporal scale. As time scale decreases so Schumm and Lichty (1965) observe,

"variables which are considered dependant during long periods of progressive erosion become independent during the shorter spans of graded time". (p.114).

This is not to assume however that independent controls which operate over large time scales are necessarily meaningless over smaller time scales. Firstly low frequency - high impact independent events such as earthquakes, catastrophic flooding etc will occur in the future and will therefore be relevant at a short time scale. Secondly long-term progressive or 'ramped' independent events may provoke short term responses - particularly where there may be acceleration in the magnitude of the event. Geological control provides a useful example to illustrate this suggestion. Nanson (1980) observes meander displacement of the Beatton River, British Columbia, as a response to accelerating eastward tilting of the Beatton Valley due to isostatic re-adjustment; Gomez and Marron (1991) observe discontinuities in planform characteristics of the Belle Forche River, South Dakota, believed to be in response to neo-tectonic activity of the Precambrian basement.

2.2.3 What can change ?

In order to develop an understanding of river channel 'change' it is firstly important to characterise the 'form'of river channel features in geographical space. Form refers to the spatial relationship between selected features of the river channel and/or the relationship between selected river channel features and other features in space.

Unwin (1993) notes that the definition of space and measurement in space is very often taken for granted in physical geography. He observes that human geographical studies, for example, are able to conceptualise 'mental' space in terms such as cultural or social space. Harvey (1969) draws attention to what he calls the "language" of space and states that, "for the most part geographers have assumed a particular spatial language to be appropriate without examining the rationale for such a choice". In the 'real world' of physical features, Unwin (1993) refers to features as occupants of 'natural' space.

Two views exist for characterising the nature of natural space, firstly, 'Relative' space considers the relationship of features relative to each other, "Space and time are dimensions that are defined by the entities that inhabit them and not visa-versa" (Raper and Livingstone, 1996, p.363).

By contrast, 'Absolute' space defines space as a container of material objects,

"A rigid framework which has existence independent of the entities." (Raper and Livingstone, 1996, p.363).

Such a definition has its roots in mathematics, geometry and physics. For example Isaac Newton described space as consisting of a framework of points and 'change' occurs as these point become occupied or unoccupied by matter. This view of space has been more generally accepted and used in geomorphology; many examples of geomorphological change characterise the movement of geomorphological features with relation to a fixed datum value (e.g. global co-ordinates such as longitude and latitude, and the Ordnance Survey National Grid). But this is not the case for all geomorphological measurement.

This can be illustrated by considering two examples:

Example 1

A meandering river where measurements of river channel planform are measured through time to determine indices of river channel change, the river channel planform is recorded as an absolute measurement in space. River channel boundaries (e.g. banktop) are measured relative to the Ordnance Survey National Grid which is defined for 'fixed' features within the floodplain such as buildings.

River channel change is therefore a reference to whether any one position in space is occupied by the river channel or not. The river channel may be considered to be changing in absolute space if points within space have changed occupancy.

Consider the same river channel now independent of its surroundings and independent of a fixed co-ordinate system. If viewed in relative space over the same period of time the investigator may observe that the 'form' of the channel remains unchanged. Meanders may retain identical radii of curvature, amplitude and wavelength even though the unit as a whole may have migrated down valley.

Example 2

River cross-sectional records present a similar challenge. Consider an example where river cross-sectional characteristics are compared through time at the meander apices and points of inflexion. These comparisons can only be realistically achieved if measurements are obtained in relative space. If the planform characteristics of the river channel have changed between observations then the meander apices and points of inflexion may no longer lie at the same location in absolute space and as such channel measurements at these locations may be meaningless. Such comparisons are only truly valid in relative space.

Measurement in space and time involves attaching dimensions to features. Unlike time, space is considered to be multi-directional and may be measured in one, two, or three dimensional form. Consideration of just 'what can change' has been addressed in several papers in terms of 'degrees of freedom' (e.g. Beschta and Platts, 1986; Hey 1978). The morphological response of any one of these degrees of freedom is determined by the interaction of the controlling variables which, were there perfect determinance, may be governed by process equations. However, the description of form and the relationships between form and process are insufficient to fully determine river channel response. For example, cross-sectional geometry may display a multiplicity of shapes determined by the characteristics of the wetted perimeter. The indeterminate nature of characterising 'what can change' arises from two principle factors:

a) The response variables do not operate independently of each other (Beschta and Platts. 1986). For example, Williams (1986) observes an inherent relationship between channel width and radius of meander curvature.

b) The relationship between form and process is determined by the scale of approach. Hey (1986) notes that in practice insufficient is known about all the process equations for this to be achieved.

2.2.4 Change.

Relationships between space and time

This section will examine the relationship between space and time in the way that it influences a perception of river channel change and river channel stability. The previous section has demonstrated that controls regulating the nature and magnitude of river channel change operate at different relative magnitudes dependant on scale in space and time. Schumm and Lichty's (1965) paper was instrumental in examining the relationship between space and time. It built on the theories of landscape evolution originally proposed by Davis (Cyclical landform development) and Gilbert (Dynamic equilibrium) at the close of the 19th Century by explaining these in the light of research contemporary for the early 1960's (e.g., Hack, 1960; Leopold *et al*, 1964). Their paper subsequently formed a benchmark in geomorphological research for subsequent emerging thought on the nature of landform change such as threshold theory, formalised by Schumm (1973), Coates and Vitek (1980), and Landscape Sensitivity (e.g. Allison and Thomas, 1993). An understanding of this work is invaluable for understanding river channel history.

Hack (1960) was instrumental in considering the relationship between space, time and landscape change by drawing on Gilbert's premise that landforms adjust to a state of dynamic equilibrium, a condition of optimal efficiency between environmental driving forces in the landscape and the landscapes resistance to change. Harvey (1969) termed this tendency for a system to move towards optimal efficiency the 'principle of optimality.' Hack (1960) observes that the elements within the landscape exist independent of time, but states that it is energy that changes with time and, therefore, landscape change may follow. This was explained by Bull (1979, 1980) who stated that the balance between driving and resisting forces may be explained as a ratio between the two opposing tendencies. Conceptually an equilibrium condition will exist when,

$$\text{Driving force} / \text{Resisting force} = 1.0$$

Substituting stream power and critical power as surrogates of driving and resisting force respectively a stream considered to be in equilibrium is one characterised by, Stream Power / Critical Power = 1.0

The premise follows that should the driving forces exceed frictional forces then conditions will favour channel erosion, should critical power exceed stream power then conditions will favour channel deposition.

As helpful as Bull's work is in order to conceptualise river channel change, in practice the concept requires closer consideration. The equilibrium concept gives only limited consideration to landscape sensitivity to adjustment. A change in stream power or critical power will not necessarily provoke a morphological response. If a response is provoked then there may be an inherent 'lag' time between event and reaction. Lags may occur as a consequence of multivariate morphological responses to several events occurring simultaneously. Mis-interpretation of scale may therefore promote misunderstanding of the nature of channel change. The notion of dynamic equilibrium (e.g. Langbien and Leopold, 1964) is therefore highly scale dependent. Bull (1980), for example, observes that over the same period in time, 'gross' landscape change may differ considerably from 'net' change. Consider, for example, the sediment budget through a given reach over a given period of time: stream power and critical power will vary spatially throughout the reach and these spatial patterns may change with time. Consequently, variable patterns of sediment erosion, transport and deposition will be experience within the reach. At the end of the period of observation, it may be recorded that there is no overall sediment imbalance within the reach. Therefore net change (as defined here by sediment balance) will be zero even though gross sediment transport (and hence work done) may be high. Such conditions are summarised by Graf (1982) who notes that a, "Lack of change does not necessarily imply lack of process, since the net result of interactions over a restricted period of observation might be zero."

Subsequent revisions to the equilibrium theory have expanded the concept in an attempt to differentiate between different observed pattern of river channel behaviour (Figure 2.5). As such conditions of dynamic and/or steady state equilibrium are confined only to short time scales. Thornes and Brunsden (1977) considered a 'floating equilibrium model', they state,

"The idea of time required, but independent of a fixed scale of events, is generally characteristic of models in which the process or assemblage of processes and the corresponding forms are (i) assumed to be poised in some condition of dynamic stability or equilibrium over the particular period of observation, or (ii) observed on a scale so short that trends, which would imply relative position, are not observable or are unimportant. generally speaking models of this type incorporate negative feedback assumptions to explain the absence of trend." (p.117).

Taken to extremes, Schumm (1991) quotes Von Bertalanffy who observes that at near instantaneous time scales the concept of history is essentially meaningless,

"In physical systems events are, in general, determined by the momentary conditions only." (p.37).

This being the case, therefore, 'history' can be considered as having only notional importance in determining future conditions. However, it must be remembered that

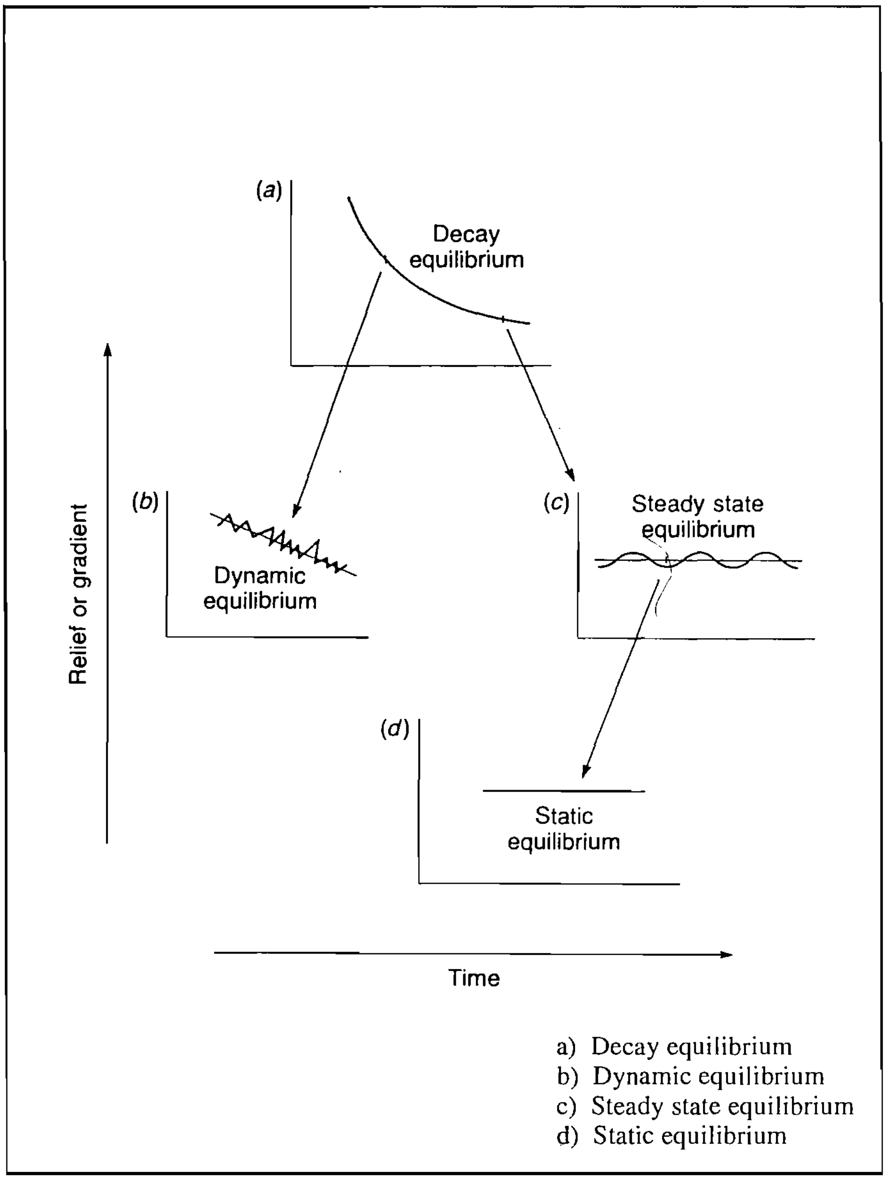


Figure 2.5 Types of equilibria (Schumm, 1991)

Perception of change is dependent on the scale chosen to represent space (relief or gradient) and time it is channel history that has determined the instantaneous condition - the sum of all prior changes at all time scales up to that instant in time.

The nature of the morphological response has been considered in terms of threshold and/ or transient response to controlling variables. A geomorphological threshold may be considered a critical limit or boundary condition which, once exceeded promotes a distinctive change in the system and may spatially separate different modes of operation (Bull, 1979; Schumm, 1973). Dependent on the nature of the controlling forces (and their interaction) that promote change, thresholds may be considered to be intrinsically promoted (internal) or extrinsically promoted (external). Events that promote change may be considered independently (e.g. a flood event) or may result as a consequence of the interaction of processes which when combined at the right magnitude may be sufficient to promote complex 'random' change in the system (Graf, 1982). Again, the notion of the instantaneous event is scale dependant, a flood, for example, may be considered instantaneous if observed on a hydrograph spanning a century, but observed as gradual rising and falling limb/s on a hydrograph resolved to hours, days or perhaps weeks. As such, Coates and Vitek (1980) acknowledge that the identification of thresholds is highly scale dependent,

"How large a change and how long a period must an event exhibit to be classified as a bonafide threshold?" (p.11).

Again, the extrapolation of the true nature of change is dependent upon the resolution at which the change is observed and will determine the perception of the

'Reaction' time (the time taken for the river channel to respond to the 'event') and 'Relaxation' time (the time taken for the river channel to assume a new equilibrium condition). If multiple events occur with relatively high temporal frequency it is quite possible that the river channel will never actually achieve a new equilibrium condition, the system may be considered to be in a condition of permanent change,

$$\text{Reaction Time / Relaxation Time} > 1$$

Such conditions are termed 'transient' (Thornes and Brunsden, 1979). A river may pass through several transient conditions as it attempts to establish equilibrium. Richards (1987) notes that under such circumstances the new equilibrium condition cannot necessarily be predicted by the conventional equilibrium model. Ferguson (1987) supports the view that channel patterns and channel changes are transient rather than defined by critical spatial and temporal boundaries. The classic paper of Leopold and Wolman (1957), for example, proposed that spatial boundaries dividing channel pattern may be classified on the basis of channel slope. Schumm and Kahn's (1972) paper supports this view on the basis of flume experiments. More recent work has demonstrated similar patterns (e.g. Erskine, 1992) but while studies have been successful at determining spatial thresholds of channel pattern, there has been less success in the identification of temporal thresholds. In particular, river channel responses cannot always be attributed to specific events - there is an inherent lack of resolution in extrapolating river channel history. Furthermore, because a river may respond in a particular manner to events in the past is no guarantee that the same river will respond in the same manner in the future.

Spatial problems may arise through definition. Leopold and Wolman's definition of the meandering - braided threshold is now seen as somewhat simplistic. Knighton and Nanson (1993), for example, notes that a definition of the braided channel is too broad and notes that there may be continuum of channel forms that may lie across this boundary.

Temporal problems may also arise. For example, Carson (1984) has demonstrated that equating channel threshold response to simply one dominant control (e.g. slope) is insufficient to determine channel pattern (in this case threshold values were discovered to vary significantly with bed and bank sediment). Ikeda and Iseya (1987) support this view through consideration of the sediment 'mixture' and acknowledged that sediment size distributions are seldom uniform in time and space. As such, they observe that the sediment "mixture can make some sections more sensitive than others." They offer this as an explanation as to why the flume experiments of Schumm and Khan (1972) were somewhat simplistic in describing threshold conditions as they assumed homogeneous sediment distributions. Therefore, it is perhaps more appropriate for the applied geomorphologist to identify historical events that may be considered 'geomorphologically effective', in the past in promoting river channel change rather than to seek individual threshold events which, while they may approximate to contemporary channel change conditions, may never be truly reproducible. The identification of historical thresholds is possibly of greater benefit to the applied geomorphologist in the identification of relative geomorphic sensitivity between reaches.

Geomorphological effectiveness refers to the notion of the linkage between what events or combination of events promote what change. In this respect landscape change may be considered a product of events of differing magnitude that occur with differing frequencies. Wolman and Miller (1960) and Wolman and Gerson's (1978) questions asked whether the 'catastrophic' low frequency - high magnitude event has a greater 'overall' effect on a landscapes development than repetitive combinations of high frequency - low magnitude events. Carling and Bevan (1989) make the observation that just because an event is rare does not mean that it is necessarily the most effective in determining the contemporary landscape. For example, Anderson and Carver (1975) studied the 'persistence' of landscape features for the Cannon Hill Valley, Exmoor. They observed that dramatic changes to the valley following flooding of 1952 were progressively obliterated by later, lesser magnitude events that followed. While the study demonstrates a 'threshold' response (the relatively rapid landscape change) to the 1952 flood there is no guarantee that a reproduction of the same flood conditions of 1952 will produce the same pattern of spatial change:

a) Intervening events have modified the physical nature of the river basin.

b) There is no account made of human-activity in the intervening period.

Anderson and Carver (1975) note that,

"In the very long term it appears that the sequence of geomorphic events *per se* is of comparatively little importance to landscape form: rather, the landscape progresses through a series of forms under the continued activity of events of different magnitudes, whose probabilities of occurrence may themselves be seen to vary over time owing to external causes." (p.253).

Establishing the relative effectiveness between different events of differing frequencies and magnitude is therefore critical to fully understanding threshold / transient responses. As such the extrapolation and interpretation of river channel history forms a cornerstone to the geomorphologists' predictive capacity.

2.2.5 River channel stability

The previous sections have demonstrated that river channel change is highly scale dependent. It follows then that the notion of river channel stability is also one that must be qualified by the geomorphologist in terms of temporal and spatial reference.

If geomorphological principles are to be effectively embraced by river channel managers then it is important that the geomorphologist can emphasise the significance of a true understanding of stability - river channels are naturally unstable, particularly when observed over extended periods of time. River channel management strategies that that can allow for dynamic variations in channel form may provide a better long term solution to river management challenges.

Typically an engineering-based definition of river channel stability has stressed the notion that a stable channel is one in which the bed and banks of the river channel are spatially fixed (Shen and Schumm, 1981). By contrast, geomorphological definitions of river channel stability need not necessarily imply a condition of rigid steady state equilibrium. Such conditions are seldom achieved; even a concrete-lined channel may experience within-channel sedimentation problems over short time scales, may fall into disrepair over longer time scales, and, may promote significant adjustment in the long term stability of adjacent reaches. Thornes (1982) for example considers that stability may define dynamic equilibrium whereby a system may oscillate about a mean value. Alternatively, stability may be considered the ability of a system to recover from a disturbance - thus, river channels may display 'change' but the rate and direction of change may be 'tending towards' stability. An example may be a reach showing patterns of recovery to, say, channel straightening; the reach may classified as 'unstable' (e.g. berm and shelf development), but may be tending towards a condition of naturalised equilibrium.

Consequently, misinterpretations of river channel behaviour have historically given rise to problems where fundamental geomorphological principles have been ignored:

a) Many engineering-based river management schemes which sought to impose stability do not achieve these aims due to shortfalls in understanding of the operation of the fluvial system and may instead promote long term instability and degrade the natural geomorphological characteristics of the reach.

b) Restriction of channel adjustment in one reach has repercussions for the stability of adjacent reaches through flow and sediment regulation.

c) Many engineering-based river management schemes have reached or are reaching the limit of their design life and are falling into disrepair.

d) The 'perception' of channel stability many have repercussions for human development, encouraging floodplain development which may promote further instability (e.g. Penning-Rowsell and Tunstall, 1996).

In overcoming these arguments it is perhaps helpful to return to the understanding of space and time and consider the relationship to channel stability.

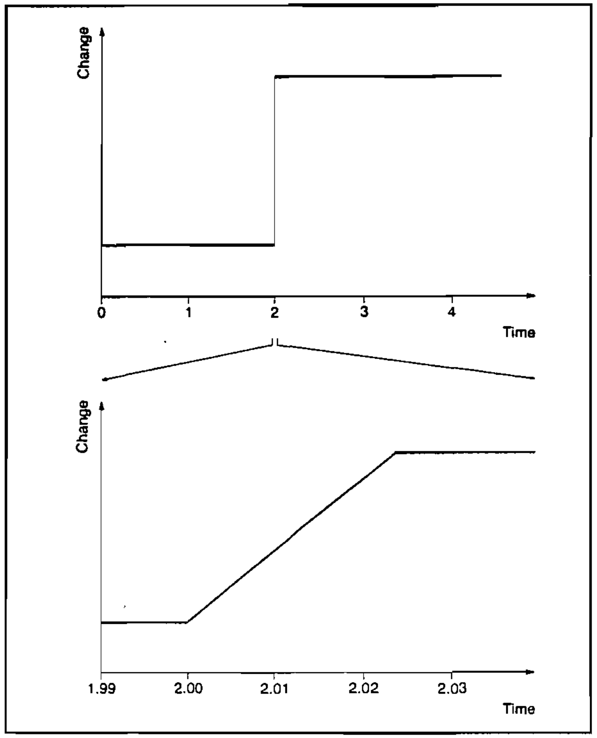
Defining river channel stability - problems in time.

Figure 2.6 illustrates that an investigator's perception of stability is highly time dependent. To illustrate this case take an example of a river channel for which bankfull width is recorded as a measured variable of channel form.

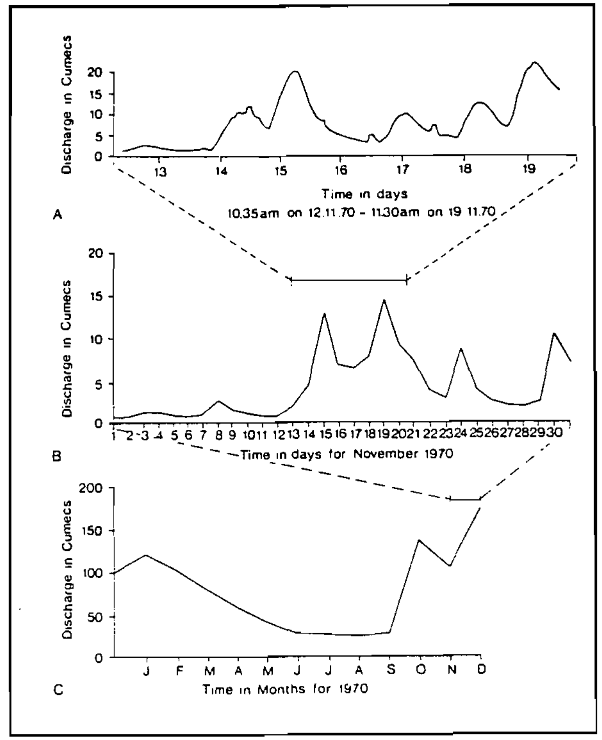
Case 1: Observations of bankfull width are recorded at discrete intervals in time over one week. The observations all record that there has been no discernible change in channel bankfull width. Channel bankfull width may be considered stable.

Case 2: Observations of bankfull width are recorded at disrete intervals of time over 10 years. The observations all record that the channel width demonstrates progressive enlargement. Channel bankfull width may be considered unstable.

Case 3: Observations of bankfull width are recorded at disrete intervals in time over 100 years. The observations record that the channel bankfull width has increased, decreased, increased, decreased ... etc., but overall net change between first and last observation is the same. Therefore, if all the observations are considered the channel may be considered unstable by virtue of gross channel change, stable by virtue of net change (dynamic stability). If only the first and last observations had been available to the investigator then he/she may have concluded that there was no change and the channel is stable.



A) An event as it appears on a time-change plot (Gretener, 1984). As the time scale is compressed so events which may appear progressive over short time scales appear more instantaneous.



B) An example showing runoff at Iping weir (Thornes and Brunsden, 1977). Instantaneous events are generalised over longer time scales.

Figure 2.6 Examples to demonstrate how perception of river channel stability is time scale dependent

Therefore, any definition of stability is temporally dependent. Furthermore, the temporal resolution of observation must be appropriate to the temporal scale over which river channel changes occur. Therefore, reference to time is important to this understanding. Ferguson (1987) notes, for example, that periods of recovery to disturbance or relaxation to an event may be mis-interpreted by the river channel manager as a long term channel change when in fact the system is stable.

Defining river channel stability - Problems in Space.

River channel change may be expressed in either absolute or relative terms. There may potentially be a degree of confusion here as the two terms may be used inter-changeably in two different contexts:

a) On the basis of measurement, dependent on the definition of space in which measurements are taken (absolute space of relative space) as defined in Section 2.2.3.

b) On the basis of the measurement of 'change' expressed as an absolute value (e.g. metres) or a relative value (e.g. a percentage).

Absolute values of river channel change may be misleading. For example, river channel width adjustments of the order of 1m/yr may not be untypical for upland alluvial channels in England and Wales (e.g. Smith, 1987). Width changes of the order of 1000m/yr are not untypical for a river such as Brahmaputra in Bangladesh (Noorbergen, 1993). While these values illustrate an absolute difference in magnitude of change reflecting the river channel's physical size they provide little significance regarding the inference of these changes. In some instances a river channel may show no discernible change in one dimension (e.g. bankfull width), yet this channel may still be regarded as inherently unstable. For example, in urban river channels this may constitute a serious flood risk where channel capacities and frictional coefficients are altered. Within-channel adjustments may constitute net imbalances in sediment transport through a given reach but show no discernible lateral planform change.

To illustrate, a case may be drawn by comparing the results of two UK based river surveys, that of Hooke and Redmond (1989) and Sear and Newson (1993). In the former, Hooke and Redmond consider the stability of 120 river channels in England and Wales based on a classification of changing river channel planform extrapolated from historical cartographic evidence. On this basis they discover, perhaps not unsurprisingly, that the majority of active 'unstable' rivers are located in upland regions of England and Wales and note that they observe that 35% of the rivers in upland Britain show some pattern of instability in the last 100 years. In the latter case study, Sear and Newson (1993) determine the distribution of reported sedimentation problems in UK rivers from an audit of river channel managers. Questionnaire returns suggest a near equal distribution of sediment related problems in upland and lowland regions of the UK.

Several observations may therefore be drawn:

a) It is perhaps unrealistic to classify river channel stability solely upon the measurement of absolute change. Absolute measurement provides useful indices for classifying geomorphological activity, but clearly is open to mis-interpretation if incorrectly applied.

b) Relative change (expressed as a percentage of the measured variable) may provide a more appropriate basis for comparisons of river channel stability. Brice (1981), for example, attempts to overcome these problems by classifying stability on the basis of percentage channel change:

Class A	Changes less than 5%
Class B	Changes 5-10%
Class C	Major local changes greater than 20%
Class D	Major general changes greater than 20%

Even so, relative measures do not in themselves provide a measure of significance. In management terms what may be considered an 'acceptable' rate of change will vary according to site specific environmental conditions.

c) Channel stability as measured in one dimension does not necessarily imply stability in other dimensions. While it is true that there may be a dependent relationship between, for example channel bankfull width and channel bankfull depth it does not necessarily follow that these two dimensions will adjust at precisely the same rate. There may be time lags between a responses in related variables (Graf, 1982). Brice (1981) makes a spatial distinction between lateral and vertical stability dependent on the two-dimensional plane of observation used to characterise channel form.

d) Channel stability is extrapolated on the basis of available information. The limiting resolution of this information will limit the ability of the geomorphologist to perceive true patterns of stability.

2.3 THE EXTRAPOLATION OF RIVER CHANNEL CHANGE

2.3.1 Introduction

The previous section has investigated the nature of river channel change as defined in space and time. Geomorphological extrapolation of river channel change is dependent on the ability of the geomorphologist to reconstruct a conceptual or mathematical impression of river channel history. Extrapolation may therefore also form a basis for predicting future river channel changes.

Schumm (1991) states that extrapolation involves the projection of known information or relationships to the unknown. Reconstruction of past events and prediction of future events can be either conceptual or deterministic/mathematical (Hey and Thorne, 1984). Conceptual extrapolation may take several forms such as empirical or stochastic based observations of past and present river channel morphology. Deterministic modelling attempts to establish the mathematical relationship between events and river channel form. A fundamental requirement of both approaches is information, this may be specific to the phenomenon under investigation or through the analogy of experience from other rivers to model predictive outcomes for a given set of criteria.

As indicated in the previous section, the predictive capability of the geomorphologist is hampered as a consequence of the limitations of the information available and the interpretative route taken in extrapolating this information. For example, relationships may typically be indeterminate as a consequence of perceived randomness and/or divergence of phenomena, or through an inability of the available information to represent the changes that are occurring. Understanding information (and not just possessing information) is a key geomorphological requirement in order to reconstruct past river channel change (Downward, 1995). This ability is dependent on three factors:

- The availability of river channel change information
- The resolution of this information
- The accuracy of this information

The aim of this section is to investigate the first two of these three requirements; namely, to examine the availability of river channel change information through a discussion of geomorphological approaches, with detailed reference to historical information, and, an examination of the value of historical information with regard to its resolution and ability to represent river channel change at different scales. The resolution of historical information is considered distinctive from its accuracy. The accuracy of historical information is considered separately in Chapter 3.

2.3.2 Methods of extrapolation

The geomorphologist has several techniques available in order to assess the nature and magnitude of river channel change. Gregory (1987) and Downs and Thorne

(1996) provide classifications of these techniques. A hybrid of this is used in this review, namely; direct and continuous observation, modelling and space-time substitution, and, historical reconstruction. A review of historical reconstruction is presented in Section 2.4.

Direct and Continuous Observation

Direct and continuous observation, as the name suggests, involves the study of river channel change phenomena directly, either by,

a) making specific bespoke observations continuously or at intervals in time which are tailored to correspond with the anticipated channel changes, or,

b) adopting a reconnaissance-based approach (e.g. Thorne *et al.*, 1996).

In the former case the geomorphologist is limited in the scope of the study by the available time scale over which observations may be made to yeild useful results but, as Gretener (1984) notes,

"The human timespan is a poor yardstick with which to assess geological timescales." (p.77).

Studies using continuous data are usually those which anticipate rapid rates of change and therefore minimise data redundancy. Technology has allowed continuous monitoring to be conducted remotely, thus reducing human involvement. Examples include automated continuous discharge measurement, or the use of

Photo-Electric Erosion Pins or PEEPS (Lawler, 1991). However, continuous observations are seldom recorded in an analogue or continuous format. Even if the time interval between observations is at a sub-second interval (e.g. conventional analogue video imagery will seldom record more than 24 images in any one second (Flight Logistics, Pers. Comm.) and the observations are still essentially discrete in time. Few fluvial phenomena will change at such rate as to require sub-second information (possible exceptions being studies of bank collapse and sediment entrainment).

The fear with discrete observations is that the geomorphologist might 'miss' river channel change/s. For example, Hooke (1979) comments on the use of manual erosion pins to observe river channel response to flood events. If the return period of individual flood events is greater than the ability of the geomorphologist to sample on-site then the river channel may change at a faster rate than may be recorded. Furthermore, Hooke (1979) notes that there may be practical difficulties experienced in the field when it may not be physically possible to make an observation (e.g. high water levels). 'Missing' observations by direct methods may result as a consequence of the typically punctuated nature of river channel changes; as discussed in the previous section, rates of change are seldom progressive such that observations separated by a uniform period of time may record no change for an extended period and then miss a sudden response. For example, with respect to bank erosion Ashbridge (1995) observes that,

"Although the mechanisms by which bank retreat occurs have been identified, it is impossible to include in such an analysis any consideration of the precise timing of bank collapse at a specific site." (p.237).

In the absence of proxy information with regard to the timing of the response the record of direct observation may not be able to delimit the moment of change. As Ager (1973) (noted in Gretener (1984)) observes,

"The history of life contains long periods of boredom and short periods of terror." (p.85).

The resolution (or sampling frequency) is important, therefore, to the value of the observations. These issues are closely related to resolution issues concerning historical information and are considered in greater detail in Section 2.4.

The period over which direct observations are made may also add to the value of the record. Several river channel change studies have recorded observations of river channel characteristics over extended periods and as such have develped a considerable database of information (e.g. Plynlimon (Newson, 1979), The New Forest (e.g. Gregory, 1992)).

Reconnaissance-based approaches are relatively new to geomorphological research and have been formalised as a means of providing information concerning river channel characteristics quickly on the basis of a ground based or aerial based survey. Non-geomorphological reconnaissance based approaches have been used for river channel studies for somewhat longer. In particular, River Corridor Surveys, have been adopted as a standardised means of obtaining river habitat information. These surveys contain an inherent degree of geomorphological information and as such may themselves be considered a useful source of indirect geomorphological information (Ash and Woodcock, 1988; Gurnell *et al.*, 1996)

Modelling and space-time substitution

Geomorphological models may take many different conceptual and physical forms. The basis of the model is to produce a simulation of reality. This simulation may take the form of a physically scaled representation of reality (e.g. the flume) or based upon the assumption of deterministic relationships between variables which may be represented mathematically in the form of an equation (e.g. regression) or computer-based simulation. As such deterministic models may simply consider the relationship between individual landscape phenomena as a bi-variate relationship (e.g. slope-sinuosity) or form multivariate relationships between several variables.

Modelling has provided the geomorphologist with a powerful means of exploring physical relationships in the natural world. However, potential dangers arise when models developed for the advancement of theoretical research are applied at face value to solving applied geomorphological challenges. The risk is that the model is accepted as 'law' either without necessarily considering all of its limitations or, without fully considering the specific conditions of the environment to which it is applied. Technology has made the tools of modelling easier and accessible to increasing numbers of water engineers and river channel managers. It is possible, for example, to buy 'off the shelf' hydrologically based models for immediate use (e.g. HYDATA written by the Institute of Hydrology, Wallingford). But there are dangers with 'cookbook' methods. If geomorphological models are applied by non-geomorphologically trained river channel managers they may give an impression of the right answer, but may fail to observe fundamental specific relationships and patterns inherent in the river system under investigation. Klemes (1986) argues that,

"Models that work well are the greatest danger to progress in hydrology .... for a good mathematical model it is not enough to work well. It must work well for the right reasons." (p.178 S).

He provides a useful analogy of the renaissance models of celestial motion of Ptolomy and Copernicus: Both models worked and allowed the navigator to reach their destination, however, the Ptolemaic model was flawed by misconception [the Earth lies at the centre of the Universe] the Copernican model worked because it was based on sound scientific principle. Therefore modelling is an effective means of extrapolating river channel changes, just as long a the applicant is aware of the geomorphological nature of the model and its limitations. As Mellquist (1992) notes,

"Qualified 'universal geniuses' are still required to apply the results of modelling." (p.7).

Space-Time substitution has been used extensively in academic studies as a means of investigating river channel history on the basis of spatial interpolation and allometric relationships, and relies upon making measurements from several areas to represent stages in time (Ebisemuji, 1991).

Two types of space-time methods have been employed in geomorphological analysis,

a) Comparing river channel characteristics from an unmodified 'control' catchment against a modified catchment.

b) Comparing river channel characteristics within the same catchment on the basis of constant allometric growth. Ebisemuji (1991) states that, "the relative rate of change in part of a system is a constant fraction of the relative rate of change of the whole system or some part of it." (p.22).

In the former case catchments are compared in order to draw analogies between the two in order to infer rates of adjustment. Quantitative indices of river channel change may be flawed because it is unlikely that the 'natural' conditions (assuming the catchment under investigation to be unmodified) of both catchments will be the same, even if they share common characteristics. None-the-less, in the absence of corroborating information (e.g. historical information) qualitative comparisons may form a useful basis on which to develop empirically based models.

The latter case has been used widely in geomorphological research as a means of extrapolating river channel histories (e.g. Hammer, 1972, 1973; Hollis and Lucket, 1976). The most common allometric relationship to be identified is that of the relationship between channel capacity and discharge. Typically drainage basin size has been used as a surrogate for discharge. For example, using this method Hollis and Lucket (1976) estimate values for Channel Enlargement Ratio 'R' for urbanised reaches within a catchment on the basis of the ratio between observed and predicted river channel capacities:

$$R = \text{Observed Capacity} / \text{Predicted Capacity}$$

However, several authors have expressed concern over the use of allometric methods,

a) These methods may provide a measure of the magnitude of change, but give no indication regarding the mechanisms of change or the nature of the river channel response to channel forming events (Richards and Greenhalgh, 1984). For example, the channel may be actively changing (e.g. recovery) to recently imposed modifications.

b) The use of surrogate values for discharge is flawed because the relationship to channel geometry may vary dependent on local conditions. For example, Hey (1978) observed that cross-sectional geometry is not accurately defined by average width and average depth, there is a, "multiplicity of shapes defined by the wetted perimeter, hydraulic radius and maximum flow depth."

c) For certain catchments it may be unrealistic to assume that there are necessarily unmodified reaches remaining on which to base allometric assumptions. Chapter 6 of this thesis, for example, presents the example of the River Tillingbourne, a rural catchment where direct human adjustment over 1000 years extends spatially from the catchment headwaters to confluence, yet none of the catchment would be considered urbanised.

2.4 HISTORICAL RECONSTRUCTION

2.4.1 Introduction

This section will investigate the extrapolation of geomorphological information from historical sources of information. Historical sources provide a unique and invaluable means of assessing river channel change allowing for the reconstruction of past changes and (in certain circumstances) to be used to produce a probabilistic model of future adjustment (Graf, 1984, Downward *et al.*, 1994). Methods of analysis of historical information are not new to geomorphological research and have been developed extensively over the last 40 years and reviewed in detail by Hooke and Kain (1982). However, despite this academic development, historical sources of information have not hitherto been investigated regarding their application in aiding geomorphological input to river channel management. Applied geomorphological studies that have utilised historical information have tended to do so on an ad-hoc basis without necessarily assessing the true value of the information or the significance given to the extrapolation of river channel changes. At a time when river channel managers in England and Wales are increasingly concerned with the restoration and enhancement of fluvial systems historical information provides a potentially invaluable aid to making informed decisions. However, there are risks involved; mis-use and assumption regarding historical information may potentially lead to misconceptions regarding river channel history. If river channel managers are effectively to utilise the full potential of historical source information then they must do so in the light of the limitations of the information sources and the methods used in their analysis. The aim of this section is, therefore, to review the nature of historical sources of information. This will be achieved through the following objectives,

a) Consideration of the resolution (in time and space) of historical sources of information. As indicated in Section 2.1, historical resolution differs by definition from accuracy which (by virtue of its significance) is considered in Chapter 3.

b) Identification of the types of historical information that may be used by the geomorphologist to extrapolate river channel change.

c) Investigate existing methods of analysis of historical information sources and the suitability of applying methods developed in academic research to river channel management challenges.

2.4.2 Resolution of historical information

Resolution refers to the scale at which observations are recorded in space and time. Section 2.2 has illustrated that river channel changes occur at a variety of scales, therefore, the ability of the historical information to represent these changes and the ability of the geomorphologist to extrapolate future changes is dependant on the information resolution closely matching those of the river channel changes. As indicated in Section 2.2.2, a mismatch between resolution and scale of change will result in an increase in geomorphological complexity or over-simplification. What constitutes a 'suitable' resolution is therefore determined by the nature of the geomorphological investigation and river channel change questions being asked. This will then prompt the geomorphologist to seek historical sources of information and appropriate techniques at sufficient resolution to match the scale of anticipated change. It is important that the scale of enquiry is determined by the questions asked and not versa. As noted with the use of modelling techniques in fluvial geomorphology and their application to river channel management, historical information must be used 'appropriately' to the nature of the enquiry. Inappropriate use by river channel managers unaccustomed to the nature of historical river channel adjustments and information sources may therefore run the risk of developing a false perception of river channel stability, instability and/or the rate and magnitude of channel adjustment. This risk is heightened if the investigator places unjustified demands on the information, for example, using computer-based approaches to develop inappropriate quantitative indices of river channel change of low confidence. As Welles (1984) (noted in Klemes, 1986) observes cautiously, "our technological successes have simply made us more efficient at being stupid." A more pragmatic approach is to first consider some of the inherent problems of resolution in time and space.

Problems of Resolution in Time

Resolution in time or temporal resolution refers to the period of time between successive observations of river channel phenomena. Section 2.2.2 demonstrated that river channel changes occur over widely differing temporal scales. Change observed in the short-term seldom occurs at a uniform rate, but rather is 'punctuated' by events of differing magnitude that may provoke river channel responses at differing spatial levels within the river channel. Only near continuous analogue observations could possibly account for all changes at all temporal scales. As such the geomorphologist must seek a compromise: a compromise between the questions asked by the river channel change investigation and the resolution of the available information. In turn, this will dictate the method/s of analysis adopted (e.g. quantitative/qualitative) and the confidence attached to the result of the enquiry. In this way the geomorphologist is asked to make a rational decision in order to optimise the available geomorphological information with maximum efficiency, minimum loss of information and (when applied to river channel management) minimal time and expenditure. Such rational decisions are not always immediately possible, particularly where the geomorphologist may have no prior indication of the rate and magnitude of river channel change for a specific site. In these cases he/she must exercise judgement based upon analogy and experience.

None the less there is a risk that the selection of information will either be of insufficient temporal resolution with which to observe more subtle changes that may occur between records or, repeated records may show no discernible change resulting in information redundancy. In the latter case information may be amalgamated. For example, hourly discharge records may be amalgamated to daily, monthly (etc.) mean discharge values which may be accompanied with a measure of variance about the mean.

Changing the temporal resolution may change the perception of river channel change. For example, Ashbridge (1995) examined river bank erosion rates and observed considerable inter site variations over short periods of time whereas longer periods showed similar patterns of retreat.

Two further observations may be noted with regard to perception,

a) The temporal resolution will vary over the period over which river channel change is studied (i.e. there are unequal periods of time between individual records). For example, an investigation of river channel planform change may discover 10 different editions of maps and aerial photographs for the 20th Century, 3 maps for the 19th Century and 1 for the 18th Century. This may lead the investigator to suspect that the rate of channel activity is greater at times where there is greater temporal resolution simply because it is these changes that are observed. This may not be the case, simply that an increase in temporal resolution allows the closer distinction of gross channel changes against net changes for a given spatial resolution.

b) Gaps in the temporal record may lead to periods of river channel change either being ignored or grossly misrepresented in the geomorphological analysis. Academic studies of historical river channel change have tended to be directed by the resolution and period of the historical source information. As such the majority of river channel change studies using historical aerial photographs and maps in the UK tend to be limited to 50 and 150 years respectively. While it is true to say that this period in history represents a post-industrial period of rapid urban expansion and channelisation that affected many of the rivers of England and Wales, it may have lead to the misconception that human-induced changes prior to, say, 1800 were of lesser geomorphological significance. However, in England, for example, Sheail (1988) states that human-induced river regulation through direct channel modification such as milling was numerous after 800AD.

Problems of Resolution in Space

Resolution in space or spatial resolution refers to the ability of the historical information to discern changes in space. The previous section has illustrated that river channel changes occur at a wide variety of spatial scales. As with temporal resolution, it is important that the spatial resolution adopted in an investigation is appropriate to the nature of the questions asked. If the spatial resolution adopted is insufficient (too low) landscape features will be generalised, therefore, subtle changes in river channel form will be missed. For example, Noorbergen's (1993) investigation of river channel planform change of the Brahmaputra, Bangladesh was extrapolated from satellite imagery. In this case the maximum spatial resolution is defined by the pixel size (in this case a maximum of 30m using Landsat Thematic Mapper images). A spatial resolution of 30m is deemed to be appropriate to resolve river channel planform locations for a river which in its braided lower reaches has a width of between 2.5 - 12km. However, clearly such a resolution would be wholly inappropriate for, say, a small tributary of the River Thames.

If the spatial resolution adopted is too high, there may be redundancy of information. Important here is the concept of 'relative scale' defined in Section 2.2.5: if, for example a channel planform investigation is attempting to discern, say, bank erosion, the question must ask at what spatial scale will the investigator look? A relative change of, say, 5% bankfull channel width may constitute a desired spatial resolution in absolute terms of 1m for an upland river channel, 0.1m for a lowland river channel. This may automatically rule out the adoption of particular sources of information. Where inappropriate sources of information are adopted without due recourse to their limiting spatial resolution mis-interpretations regarding the geomorphological stability of the river channel will arise.

2.4.3 Historical sources of information

An historical source of information is any form of representative information that contains information pertaining to river channel history.

Sources are commonly called 'documented sources' of information indicating that these sources are in some way of a documentary nature as distinct from information that may be gleaned from an *in-situ* field investigation.

Historical information can be considered to be of three types,

a) Information that relates directly to the form and character of the river channel (e.g. a map depicting the location of the channel banktop).

b) Information that relates to historical events which may be deemed deterministic in promoting river channel responses (e.g. rainfall data).

c) Proxy-information that relates to the river channel indirectly for which there may be an inferred relationship to either form of process (e.g. estimation of urban land cover from an aerial photograph).

Clearly, certain historical sources if information may contain multiple types of information. However, sources of information are seldom recorded for the purpose of channel change enquiry.

The resolution of the historical source of information will vary tremendously according to the nature of the historical source. Typically the more abstract the source of information from the purpose of discriminating the river channel the poorer resolution of that source. The type of information source will also determine how far back in history the channel will be recorded. There may be a geographical difference to this too: in England and Wales this record may be extended much further than, for example, the United States.

Despite widespread use of historical sources of information in academic river channel change investigations surprisingly few authors have considered the nature of historical information in detail (exceptions include Hooke and Kain, 1982; Petts *et al*, 1989; Trimble and Cooke, 1991).

Types of historical information

Hooke and Kain (1982) categorise historical sources of information on the basis of the means by which information is recorded, namely; graphically, written and statistical.

Graphical representations have received the greatest amount of attention in geomorphological studies of river channel change. Graphical representations present an image of reality that closely fits to the mental image we construct in our heads when we view a river channel. The image we view on the page or the screen can essentially be considered a descriptive model of reality. This model may in some way be simplified or generalised, or modified in some way.

Casti (1997) provides an analogy regarding graphical/visual representation. He compares the image of Gertrude Stein painted by Picasso (with green hair) and a photograph taken of her in the same year. Casti asks, "which will be the better representation, the portrait or the photograph?" In reply, he suggests that the answer lies in the questions that are being asked. If the question is one of physical characteristics the painting may considered relatively poor, but if one of emotive value, in capturing the "essence" of reality then the painting may be of greater informational value. In the same manner then, while paintings may not be considered particularly valuable in terms of their spatial accuracy they may be considered valuable in providing the viewpoint of the artist and the provision of proxy-information. For example, the public perception of the 'natural' river channel is more likely to have a closer affinity to a Constable painting than to an Ordnance Survey map.

Written and statistical representations may take many formats. In some cases, graphical representations will be supported by written or statistical information, or, statistical and/or written information may be extracted from a graphical or written source of information. The distinction proposed by Hooke and Kain (1982) may not be so clear-cut.

2.4.4 Methods of extrapolation

This section does not intend to investigate specific methodologies which may be used in the extrapolation of historical river channel change because specific examples are provided in this thesis (Chapters 4, 5 and 6) and the existing academic literature has already demonstrated their contribution to academic geomorphological research (see Appendix 1). This section presents methods, particularly in considering the choice of method, at a more conceptual basis.

Above all, the choice of appropriate methods for extrapolating river channel change information from historical sources is determined by the nature of the river channel change questions asked. In particular, in applied geomorphological research, the requirement for the investigator to seek methodologies fitting of the questions asked and not simply utilise the available historical information is important. If the investigator believes that the answers to the specific questions may be met fully and accurately from a relatively simple (possibly qualitative) methodology then there is no immediate requirement to make the investigation more complicated unless it may be demonstrated that this may potentially yield additionally valuable information within the terms of reference of the investigation.

Hooke and Kain (1982) note that there are four stages to the analysis of historical information (Figure 2.7):

- Reconstruction of the chronology of the changes
- Reconstruction of the rate of change
- Classification of the rate of change

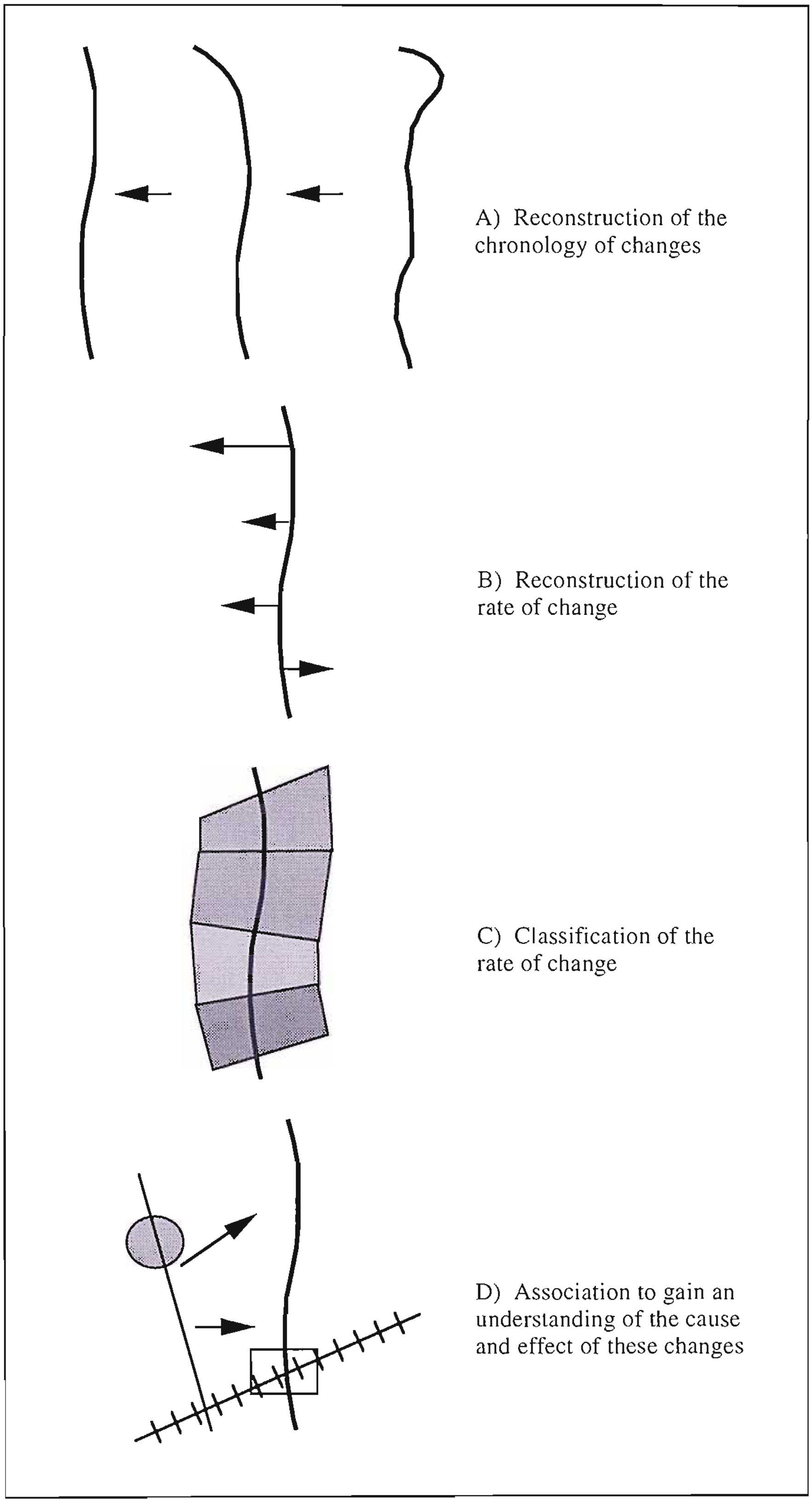


Figure 2.7 Stages in the analysis of historical information (Adapted from Hooke and Kain, 1982)

- Association to gain an understanding of the cause and effect of these changes

This is supported in that the majority of academic geomorphological studies of river channel change have been quantitative in nature. This is not surprising in that quantitative analyses may provide a more rational means for classifying the rate of change and/or presenting information in a more deterministic basis.

A risk with quantitative analysis of river channel change is that the results of the analysis may often be lauded as 'truth' without due consideration to the limitations of the information. Definitions of, for example, stability which are obtained from quantitative indices must be careful to define the context and confidence with which these indices are obtained.

Qualitative approaches have been somewhat ignored in geomorpholgically based river channel change investigations. Indeed, qualitative approaches in physical geography as a whole have received less attention when compared to, say, human geography.

Somehow the assumption is made that because a study may be qualitative then it may in some way be unscientific and possibly undervalued, "arm-waving" geomorphology (Downs and Thorne, 1996). This notion is considered in greater detail in Chapter 7 which highlights challenges to promote geomorphologically sensitive river channel management.

Qualitative studies may yield important river channel change information for two principle reasons,

a) The nature of the historical source information may not lend itself to quantitative analysis. Rather, the comparison of historical material may allow the investigator to develop a mental image of river channel change and provide a historical context for contemporary observations. This may typically be the case where the investigator wishes to use many disparate sources of information (e.g. Chapter 7 provides an example for the investigation of the River Wey). In these cases the historical information may also provide useful proxy-information concerning catchment wide change and development which may be related to contemporary characteristics.

b) Historical information which would otherwise be used in a quantitative analysis may be of insufficient resolution reliably to provide quantitative indices to delimit river channel change. However, the information may still be used to infer the 'direction' of change. For example, NRA (1993) discovered that traditional map based attempts to quantify river channel planform change for the River Hogsmill, Surrey, were of insufficient resolution to discern reliable indices due to the size of the channel width representation with respect to map resolution. However, these maps proved helpful in providing qualitative information concerning historical channel re-alignment and providing proxy-information concerning catchment wide change over the last 150 years.

2.5 CONCLUSIONS

This chapter has investigated several key issues concerning the nature of river channel history, river channel change and the extrapolation and reconstruction of change. The chapter opened by considering Gregory's (1987) river channel change questions and observes that as the complexity of the question increases, so the ability to answer the question becomes increasingly challenging. Straightforward answers allowing prediction are not possible because seldom is linear system behaviour observed for river channel change. As the complexity (which as been shown to be closely related to scale) of the system increases so the response of the system becomes more uncertain. Uncertainly increases further when there is only limited information with which to reconstruct past changes and the more complex the system the greater the required resolution of the information if the system response is to be estimated. Furthermore, this chapter has demonstrated that historical sources of information typically will only record a particular dimension of river channel change (e.g. planform) whereas the system response itself is multi-dimensional to many contributing processes. Therefore, increasing the resolution of observation (in both space and time) will provide a greater understanding of the complex nature of the system, but this does not imply linearity.

The applied geomorphologist is therefore somewhat at odds with the river channel manager who has historically hailed 'prediction' as one of the most valuable elements in the management of the river landscape. The examples explored in this thesis examine this premise. Importantly, it is not the purpose of the examples chosen in the following chapters to attempt to attempt to 'predict' future adjustment, instead, they serve to estimate 'patterns' of behaviour and the propensity for change in the future. Prediction is therefore not about determining absolute response but rather is about estimating the likely boundaries within which future changes may manifest.

Following this argument, the notion that a qualified response to a river channel change question should be of any lesser value than a quantified one is invalid, it is simply different. Provided that source information is investigated in a systematic manner with careful consideration as to the limitations of this information (with respect to its accuracy and resolution) then a qualitative evaluation of the information yielded may ultimately prove as valuable to applied geomorphological research as quantitative evaluations. Indeed, the very concept of quantification implies an 'absolute' and results are only truly valid where confidence limits - boundaries of uncertainty - can be attached to these results. These boundaries may themselves be qualitative in nature, expressing the conditions and limitations with which the quantitative expressions are obtained.

The choice of case studies reflect the availability of historical information in order to illustrate these techniques. Moreover, the case studies serve to illustrate the nature of change itself in the systems concerned at various scales of operation and as such provides a link between what may be considered 'pure' or theoretical geomorphology (as reviewed in this chapter) and their application.

2.6 SUMMARY

The contemporary river landscape owes its geomorphological characteristics to its history that may be considered at a range of spatial and temporal scales.

Historical perspectives provide a basis for understanding geomorphological change through an appreciation of space, time, scale and resolution. The characteristics of river channel change and river channel stability are scale dependent.

Extrapolation of river channel change is multifaceted. The geomorphologist has several techniques at his/her disposal. Historical approaches provide one such way of reconstructing river channel history but their value has not been fully recognised in their contribution to applied geomorphological research.

Historical information is limited by the ability of the information to reliably yield river channel change information. This is dependent on the selection of appropriate information to the river channel change questions being asked, the information resolution and accuracy and the adoption of an appropriate methodology.

CHAPTER 3

ERRORS AND HISTORICAL INFORMATION

3.1 INTRODUCTION

The previous chapter has investigated both the nature of river channel change and has introduced the means by which the geomorphologist may utilise historical sources of information for understanding river channel changes at a variety of scales. Chapter 2 noted three factors that influence the value of historical sources of information:

- The nature and the availability of the historical source information
- The resolution of this information
- The accuracy of this information

Chapter 2 investigated the first two of these factors. This chapter will specifically investigate the accuracy of historical information sources and the errors arising from the extrapolation of river channel change information and attempt to determine of the significance of these errors to limiting the effectiveness of applied historical river channel change studies. This will be achieved through the following objectives, to assess:

a) The classification of errors

b) Inherent errors in historical information

c) Operational errors in the analysis of historical information

d) The propagation of errors in the determination of river channel change

All geographical information contains error. Error is a fundamental element of all historical information and this error is incorporated when historical information is employed to identify river channel change. The analysis procedure itself may introduce further errors as well as the possibility of magnifying existing errors. However, if the geomorphologist can accept that all information will contain an element of error and is able to distinguish their magnitude and direction then a decision may be taken regarding the confidence of the final result of the analysis. This may be expressed as a measure of Total Error, and may be expressed quantitatively or qualitatively. It is important is that an understanding of the nature and magnitude of error will allow the geomorphologist to attach levels of confidence to the results of river channel change analysis. The expression of Total Error may be expressed in absolute terms (e.g. metres) or relative terms (e.g. a percentage of the total channel change value) and its dissemination will provide a basis for which the true significance of change can be assessed. the ability to distinguish 'real' changes from the 'noise' of combined and propagated errors. If the total sum of all the component errors involved in the analysis of historical river channel change exceeds an acceptable level of tolerance for a particular study then the identified changes may have little significance for developing an understanding of the river system. Levels of tolerance and the significance of errors are determined, in part, by the nature of the questions asked of the geomorphological analysis.

Therefore, the greater the complexity of the questions being asked, the more rigorous the procedures for extracting the required information and the less confidence in the result. Procedures outlined here for attempting to determine the level of the errors and the level of confidence that may be placed on the result may help to remove a degree of subjectivity from the procedure of accepting of rejecting the results of the river channel change analysis.

This chapter does not intend to set out specific methods of historical analysis or methods for the testing for errors (these have been reviewed, for example, by Hooke (1984), Hooke and Kain (1982) and Lawler (1991) and specific examples are considered in Chapters 4,5 and 6. Instead, this chapter develops arguments drawn from a range of geographic disciplines (e.g. cartographic theory) to outline the theoretical principles through which errors are transcribed through collection, handling and analysis.

3.2 CLASSIFICATION OF ERROR

Error may be defined as, "an act involving an unintentional deviation from truth or accuracy." (Websters English Dictionary, 1993). In this case 'truth' is considered to represent the 'real world' or source of information and as such extrapolation errors of river channel changes represent the deviation of the geomorphologist's understanding of change from 'true' reality.

Accuracy refers to a freedom from mistake or, "the closeness of observations, computations or estimates to the true value as accepted as being true" (AGI, 1998).

Accuracy may be classified in terms of its type or by reference to the entities it represents (e.g. spatial, temporal and/or thematic). Accuracy differs from 'precision' which refers to the exactness of expression regardless of whether these values are right or wrong (AGI, 1998).

Accuracy and precision differ fundamentally from resolution as described in the previous chapter. Resolution determines the ability to resolve river channel phenomenon in time and space. As before-stated, a record of river channel change may be spatially and temporally 'accurate' but may be of insufficient resolution confidently to determine change.

Errors may be classified by type as gross, systematic and accidental or as inherent or operational (e.g. an error may be classified as a gross operational error). Such as classification by typology provides a useful basis for understanding errors involved in the extrapolation of river channel change information from historical information adopted in this chapter.

3.2.1 Gross errors

Gross errors are mistakes. Gross errors may manifest themselves in an obvious manner (e.g. a mid channel bar that rises outrageously from the representation of the river channel) or may be more subtle and possibly remain undetected. Gross errors may be minimised by adhering to routines and checks in order to attempt to identify obvious mistakes and as such errors of this type can never be completely discounted.

3.2.2 Instrumental errors

Instrumental errors arise from inherent limitations of the instrumentation used to record river channel features. Spatial instrumental errors may result in the recorded value differing about the true value. For example, measurement of a pebbles long axis with calipers will produce estimates that are greater than or less than the true value with limiting spatial resolution to the expression of the measurement (e.g. micrometres, millimetres etc.). Spatial instrumental errors may also produce measurements which are consistently greater or smaller than the true value. For example, a metal tape used to measure bankfull width will provide differing measurements as determined by its coefficient of thermal expansion. Certain instruments will allow for such errors and suggest optimal operating conditions. Temporal instrument error may show a similar pattern of behaviour. For example, a stopwatch that is consistently fast will produce measurements which have consistent relative error. If the nature of the discrepancy is known then the error may be accounted and its magnitude and significance estimated.

Instrumental errors may consist of individual or component errors which make an overall assessment of the Total Error more difficult. Take, for example, an aerial photograph which will exhibit instrumental errors in both space and time. In space the image of reality that is produced on the photographic film will deviate from 'true' through the introduction of planimetric and scale distortions in the image as a consequence of the camera used to obtain the image; the camera lens will introduce optical distortions (e.g. spherical and chromatic aberrations), the movement and vibration of the camera by the aircraft, camera mount system and shutter mechanism. All of these instrumental effects will affect and limit the ability of the operator to capture imagery that is error free, regardless of the systematic process adopted for data capture. Estimating the value of the total instrumental error in this case will require the investigation of each individual component error and their relationship.

3.2.3 Systematic errors

Systematic errors are potentially the most complex errors to appreciate and to quantify. Systematic errors are those errors that are introduced by the system used to transcribe information from the real world into a model of this world. A map for example may be considered a cartographic model of reality whereby abstract lines and symbols are used to represent reality. The use of the term 'model' here is a conceptual one. The map, for example, is a representation of reality but in terms of its physical entity bears no relationship to the river. Instead, the understanding of the river channel is a function of the 'language' of communication (Robinson and Petchenik, 1975). Systematic error is a product of the 'route' taken for analysing information and the complexity of the answers required (Figure 3.1). The nature of systematic errors may therefore vary considerably and are a function, notably, of the means by which the information is recorded and analysed. Thapa and Bossler (1992) note that the presence of systematic errors may produce measurements that are precise but not necessarily accurate. Therefore, different investigators may work precisely yet may be consistently inaccurate.

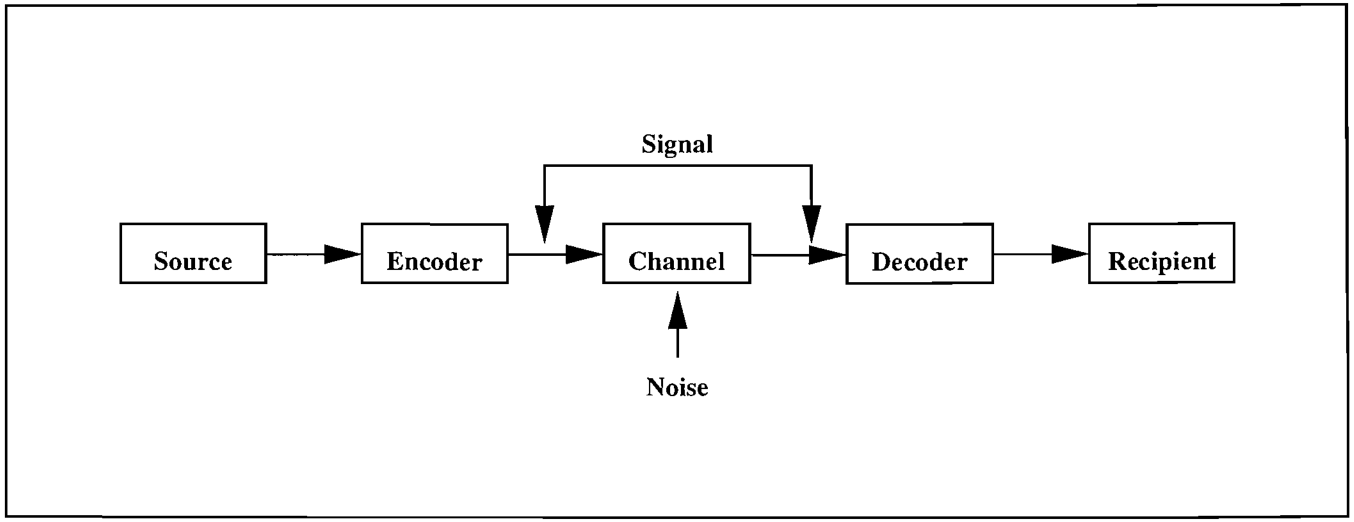


Figure 3.1 The fundamentals of a communication system (Robinson and Petchenik, 1975)

Information from the source (the 'real world') is transcribed to the recipient (the investigator) via a channel or means of communication. The encoder represents the method used to transcribe information to the channel, the decoder to interpret the information from the channel.

For example: river channel form may be surveyed for the purpose of producing a map to represent this form. The encoder is the system used to produce this map (the survey and cartographic method). The map represents the channel. The decoder represents the operational system used by the investigator to reconstruct river channel form.

'Noise' consists of interference to the signal and constitutes the error associated with information transcription.

3.3 INHERENT ERRORS

Historical information provides a record of the characteristics of the landscape at a variety of temporal and spatial scales. Inherent errors are those errors that are presented to the geomorphologist immediately prior to analysis and therefore consist of error arising from the:

- original collection and recording of information
- the representation of this information (e.g. the model used)
- the storage of information

3.3.1 Recording Information

Historical information is seldom collected and recorded for the purpose of historical river channel change investigation. Consequently the system of information collection may bear little or no relation to the accurate recording of river channel features. Perception of the river channel feature on the part of the 'surveyor' (the term is used loosely to embrace those who would record river channel information) may result in widely inaccurate estimates river channel features. Errors arising from the collection of information is therefore a product of the ability of the equipment to measure precisely (e.g. consistently, to the same degree of error) but also of the ability of the surveyor to perceive river channel features.

Two scenarios may be envisaged dependant on the relationship between instrumental and systematic errors.

a) The ability of the surveyor to perceive the nature of the river channel is greater than the resolution used measure river channel features. For example, consider the measurement of gravel bedload; give the surveyor a simple ruler and the measurements will be limited to, say, the nearest mm of the true measurement. Give the surveyor a micrometer and the measurements may be accurate to the nearest sub-millimetre of the true measurement.

b) The ability of the surveyor to perceive the nature of the river channel is less than the resolution used to measure river channel features. For example, consider the field measurement of river channel sinuosity. Errors in measurement arise, not necessarily because of the equipment used to measure distance, but because of the ability of the surveyor precisely to define the meander sinuosity. In this sense, a field measure of meander sinuosity made with a fabric tape may potentially be as accurate as one made with an Electromagnetic Distance Measurement (EDM) device.

The following points may, therefore, be made:

a) Systematic errors are greater where the perception of the phenomenon requires subjective judgement.

b) Systematic errors are greater where the resolution of measurement falls below that of the surveyor to define river channel phenomena.

All surveyors will have differing perceptions of reality dependent on their understanding of the phenomenon to be recorded. In some cases (e.g. the artist, painting a picture) the conceptual model formed has no concern for topographic accuracy. In cases where the surveyor is aware of the requirement to preserve topographic accuracy this may involve working to definitions of landscape features which must be interpreted in the field. For example, Harley (1975) notes that the Ordnance Survey will usually define the banktop position as that of the 'normal winter level', although the degree to which this boundary may be perceived in the field is dependent on the precision of the surveyor to work to a consistent level of confidence. As different maps are likely to be surveyed and revised by different surveyors adhering to consistent interpretation of definition is important. Downward (1995) conducts an experiment to illustrate the effects of surveyors' perceptual errors. The experiment was conducted on the Highland Water, Hampshire, to obtain and compare the results of cross-sectional measurements by repeat survey of the same cross-sections by different surveyors all instructed to conduct the topographic survey to the same definition - that of the 'banktop'. Using the same equipment and survey method four cross-sections were surveyed independently between three and six times by three different surveyors. From the results of the repeat surveys it is observed that the estimate of channel bankfull widths is the most sensitive to positional error (one cross-section was represented at a bankfull width of between 5.31m and 11.5m) greatest errors were observed for increasing width-depth ratio. In this experiment the equipment and the survey method is constant. The same cannot be assumed for historical sources of the same format which may alter over the period of the historical record. Increased technology does not, however, imply increased accuracy, as Carr (1962) observes, "Improved equipment and plotting merely showed up more glaringly the errors caused by accident and misrepresentation which were surely always present."

3.3.2 Representation of information

Historical information may be represented in a variety of formats. Representation of reality involves the formation of a communicative model which may be graphical, written or statistical (Hooke and Kain, 1982). The model will never represent reality without information loss and will involve the generalisation of reality to record phenomena of interest. These phenomena need not be specifically river channel features. Errors may be introduced as a consequence of spatial and/or temporal mis-representation.

Spatial mis-representation

Generalisation of information attempts to preserve the 'essence' of reality. The level of generalisation will determine the spatial resolution of the record (e.g. the scale of a map or the number of cross-sectional measurements for a given capacity of channel).

The generalisation of the image may involve the distinction of symbolic notation to define river channel features. For the map this is the point, line or polygon (e.g. the spot height, the river channel boundary line or contour). This information need not necessarily be represented graphically but instead locational values may be tabulated as individual points, lines and polygons containing attribute information.
Information may also be represented in 'virtual' space (Casti, 1997). Digital

representations and construction of reality differs substantially from those of the real world. The model that is formed in the computer does not exist in any real sense, it represents a virtual world that is defined by co-ordinates and attributes. These co-ordinates may be recorded in absolute or relative space. For example Computer-Aided Design (CAD) representations of reality may present the river as a self contained entity with no connection to the outside 'world'. Other Geographical Information System (GIS) -based models may try to tie the representation of the river channel into a fixed co-ordinate system (e.g. longitude, latitude and elevation above a given height datum).

In nature, boundaries are purely conceptual and do not strictly exist. Maffini *et al.* (1989) note that for a given scale of presentation, vector representations assume a precision that does not occur in reality, whereas cellular formats provide a generalisation of nature. The 'line' therefore is a boundary which may represent an absolute division between two entities. In reality the river channel boundary locations between different entities are described as 'fuzzy', that is to say they lie in the proximity of the boundary and the line itself may be considered representative of the location of maximum probability that a transition between two entities exists for a given scale of representation (the fractal dimension, see Chapter 2).

The boundary may be considered at two levels (see Figure 3.2):

a) The boundary condition may be considered at a nominal level to indicate presence-absence. For example, the channel boundary condition may be considered to divide the 'river channel' from 'non-river channel': in reality this river channel boundary is totally abstract. The geomorphologist will consider the transition from

Surveying river channel cross-sectional form

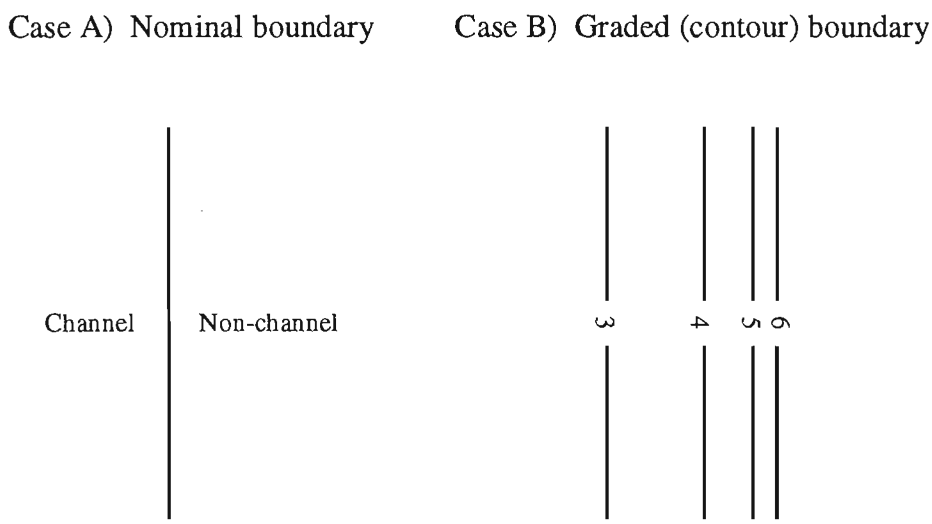


Figure 3.2 Graphical planform representation of the river channel boundary location

river-channel to floodplain as a boundary which may be defined in topographically (on the basis of channel form), hydrologically (on the basis of channel stage) or sedimentologically (based on sediment characteristics). The definition of a nominal boundary condition may also be somewhat unhelpful to the geomorphologist as it may potentially convey the impression to the non-specialist that the river channel system is one which is contained entirely within the bounds of this boundary.

b) The boundary conditions may also be represented as transitions or gradients. The line may be used to represent locations of equal value. As such the line is representative of a class boundary. For example, the 'contour' represents a boundary spatially dividing values of height above and below a threshold. The contour interval refers to the number of classes used in the representation and the greater the spatial resolution the greater the contour density. However, it must be remembered that just because a point may lie mid way between two contour lines is no indication that this point lies at the mean of the two heights. For example, estimates of river channel long-profile is typically represented poorly in planform. The extrapolation of channel gradient for any given point on the watercourse takes no account of localised adjustment of gradient between adjacent points (e.g. abrupt spatial threshold change) but simply represents the net change between the two contour lines.

In some cases the inherent source of information makes no demand on the surveyor to provide an interpretation of river channel features. For example, remotely sensed information is essentially free from the surveyor's perceptual errors because the information content of the image conforms to a rationalised set of criteria: A photograph, for example, will simply record information to the given parameters and limitations of camera, film and/or pixel array and system of data capture. The level of generalisation is imposed automatically by the camera, and, while the camera operator may chose the particular camera parameters to meet the requirements of the photograph, once chosen it is the river channel change investigator who will have the opportunity to further generalise the image and possibly define datum values within the image for comparison.

Not all graphical representation are necessarily resolution dependent. A representation may be topological and present the impression of form without adhering to a strict scale representation. For example, features may simply be sketched, possibly as a means of illustrating information which is presented in written or statistical form. The River Corridor Survey is one such means of representation whereby river channel phenomena may be annotated to a topological basemap representing river channel planform (e.g., Gurnell *et al.*, 1996).

Temporal mis-representation

Temporal errors of representation may occur as a consequence of generalisation in the time at which information is collected. For example, a map will show a publication date, but this may differ from the date of the survey. The survey date may be shown but this is usually generalised to the year in which the survey was undertaken. Different editions of Ordnance Survey sheets were often made on a revisional basis and so care must be taken to investigate, where possible, when different areas of the same sheet were revised. Problems arise with temporal errors of generalisation when the investigator wishes to compare two historical sources of information. For example, if a comparison is made between surveys conducted in, say, 1980 and 1982 it is possible that the survey may be separated by as little as 13 months (December 1980 to January 1982) or nearly 3 years (January 1980 to December 1982). This may have considerable implications when estimating mean rates of channel change (e.g. annual lateral migration). Other means of representation provide an enhanced temporal resolution. Aerial photographs, for example, will typically include a series of flight sortie details which may include the time the frame was obtained on the negative image.

3.3.3 Information storage

Information storage refers to the way in which historical sources of information are stored to the point where they are acquired by the investigator. The format in which the image is stored, the method by which the image is stored and the period of storage may all affect the quality of the representation and potentially affect the inherent error. The two most likely means of information storage are paper and digital formats.

Paper

Paper has been used for centuries as a medium for storing information. The longevity of paper records, despite its shortcomings, is testament to paper as a robust means of storing information. Paper is at risk from extremes of temperature, light and humidity which may affect the physical dimensions of the sheet (e.g. producing differential shrinkage and expansion) and may affect the inks or chemicals used to make a visual impression on the paper surface which may, over time, lead to fading and loss of contrast (e.g. historical photographs). Graphical information may rely on the inherent stability of the sheet to preserve the scale of representation. The physical limitations to which graphical information may be represented on paper (e.g. how close can two lines be drawn parallel but still be distinguished as two) will also influenence the scale of representation and the accuracy of this positional information. Therefore, absolute positional errors arising from differential storage errors are greater for features represented at smaller scales than at larger. For this reason, all other factors being equal, where the same information is available at different scales of representation, captured from the same original survey, it is preferable (dependant on the nature of the geomorphological enquiry) to use the larger scale of representation. A larger scale of representation does not necessarily imply a lesser level of generalisation, although Lawler (1993) notes that 1:25 000 scale Ordnance Survey sheets will depict river channel widths as constant values below a given threshold. Topological graphical representations, written and statistical records which are stored on a paper medium do not suffer information loss with time unless the paper is degraded to the point where the ink or type is no longer discernible.

Digital

If consideration is given to the period with which information has been stored in a paper format, by contrast, digital storage is relatively new. As such, there tends to be a perception that digital information storage has advantages over paper storage, but in the long-term it will be interesting to note if information stored on a computer disk will remain un-corrupted for the same period as an identical record stored on paper. Certainly digital storage allows reproduction of material without information loss, a substantial reduction in the physical size of the record and relative ease of manipulation and handling. For example, information may be transferred electronically between investigators. In theory, where information is stored on publicly accessible databases this will mean greater ease of access and significant reduction in time.

3.4 OPERATIONAL ERRORS

Operational errors are errors that arise through the process of analysis of the historical information sources. Regardless of the nature of the technique employed in the analysis, operation errors cannot eliminate inherent errors (error inherent in the historical information source) Vitek *et al.*, (1984).

However, operational techniques may potentially allow the geomorphologist to assess the magnitude of error, its direction and significance.

3.4.1 Information acquisition

Information acquisition refers to the process by which the investigator obtains the historical information. This is the investigator's first contact with the information and represents the divide between inherent and operational errors. Information acquisition will determine, 'what' information is selected, over what period, from 'where' the information is to be obtained and 'how' the information is to be obtained. The systematic or rational process by which these decisions are taken with respect to the river channel change questions being addressed and may potentially have a fundamental affect on the results of the river-channel change analysis.

It is important that the nature of the inquiry is driven by the questions asked and not by the available information of particular technique. In certain cases the applied geomorphologist may have a degree of flexibility over the 'questions' asked, particularly if he/she is involved in shaping the project design as part of a management group. Given that the geomorphological investigator is likely to have greater understanding of the nature of 'which' questions are easier to answer more fully than others it is important that he/she is able to anticipate and indicate to the river channel manager/s the limitations of the information. In this way, realistic questions may be asked and realistic expectations may be met by the historical geomorphological inquiry.

The fewer the number of stages of information transcription, the less the likelihood that information will be lost. Where possible it is helpful to obtain historical information in an original format. Where material cannot be obtained in original form it must be reproduced. Where reproduction is concerned it is important to understand the nature and magnitude (and by implication, the significance) of information loss. Typically material is deposited where it may not be accessed directly in original format and must be copied in some way. Dependent on the nature of the information there will be varying degrees of information loss. In the absence of gross errors, written or statistical information may be transcribed without information loss. For example a series of x and y co-ordinates may be transcribed from original to reproduction by, for example, copying a table of data or copying a computer disk. Graphical information in a non-digital format by virtue of format (paper-based maps, paintings etc.), size and potential uniqueness may not necessarily be obtained in original format for analysis. Alternatively, the depository may place restriction on access or means of reproduction. For example, The Tithe Survey Map for the Royal Borough of Kingston upon Thames that is held at the Surrey Public Records Office (PRO), measures nearly 5 metres in length and may only be reproduced by pencil tracing or photography (some PRO's may place a ban on photography). Other depositories may provide map sheets already in a copied version of the original. The British Library Map Office, London, for example, provides 1:2500 scale maps in microfiche format in the first instance. Wherever possible it is desirable to extract the desired information from an original document as this reduces the potential for further loss of information through two-stage reproduction. In some cases versions of the original document may be held at several depositories allowing the investigator to chose the optimum. For example, the six inch series sheets for the River Towy, Dyfed, (investigated in chapter 4) may be found in the public domain in original format at; the British Library (London), National Library of Wales (Aberystwyth) and the Carmarthen Public Records Office. Each depository tends to have a slightly different policy regarding access and reproduction of original material. The final choice is usually a trade off between the preservation of original information and cost and time involved in obtaining the desired material. Copies that may only be obtained at the depository which have already been reproduced from the original are subject to errors involved in the reproduction process.

The investigator has several different means at his/her disposal for transcribing information at the depository. Each method has its advantages and disadvantages with regards the preservation of information.

Tracing

Tracing provides a 'technology free' means of reproducing graphical representations. The loss of information is high by comparison to other methods considered, particularly if the investigator is attempting to trace from, say, a photographic image where the investigator must chose to generalise information presented in the original. The medium onto which the image is traced may also be important. Low expansion plastic based films may reduce errors associated with moisture related differential shrinkage and expansion of paper.

Photocopying / Scanning

Photocopying may produce a more faithful representation of the original map than tracing depending on the nature of the photocopier and the image being reproduced. Photocopiers will generally introduce planimetric errors to the copied image which are dependent on the nature of the photocopier. For example, small format photocopiers (typically to A3 size) using a lens to focus a new image introduce lens aberrations to the copied image. These aberrations may be chromatic in the case of colour photocopying (e.g. of colour aerial photographs). Colour imbalances may emphasise certain channel features at the detriment of others and may potentially mislead the perception of the investigator. Lens aberrations may be spherical / astigmatic effectively distorting the image such that the scale of the representation is variable by comparison to the original across the reproduction. This pattern of planimetric distortion may be complicated further where a large original sheet must be photocopied in several sections. Attempts manually to 'edge match' these photocopied sheets emphasises the nature of the distortion. If a series of photocopied sheets representing the same watercourse are to be digitised the investigator must decide whether to digitise each sheet separately with independent ground control coverage in each photocopied section of the watercourse or physically to edge match the images together prior to digitising. The former method is recommended as it preserves the planimetric integrity of the 'overlap', but may be impossible to achieve if individual photocopied sheets are lacking in suitable ground control features.

Large format photocopiers (e.g. rolling drum copiers) by their nature suffer minimal spherical distortion but are seldom found in the depository (and are somewhat too unwieldy to take along).

Finally, photocopying reduces the resolution of the original image. Line-art representations fare better than photographic representations. Attempts to define channel features using photocopies of photographs exhibit much increased loss of information and ability to identify subtle features. High definition photocopiers provide a more realistic reproduction of an original but as with rolling drum photocopiers are unlikely to be found at the depository.

Scanning directly from the original provides a further method of copying from an original image. Few depositories have scanners at present that are capable of scanning to a required data format at required scan resolution. However, a portable scanner and laptop computer have sufficient portability to take to the depository - although there is a mixed reaction from depository staff to this practice.

Photography

Reproducing an original photographically may offer the investigator the best opportunity to record the original with minimal information loss. For example, the author produced the cover of the 1998 IBG/RGS Annual Conference brochure from a photographic reproduction of the Kingston upon Thames Tithe map depicting the River Hogsmill which was taken using a high quality camera and mounting rig and using professional photographic lighting equipment. A similar set up may not be so easy to achieve in all instances. The attitudes of various depositories to photography tend to vary tremendously, from outright refusal to allow their materials to be photographically reproduced to genuine enthusiasm. This will have a significant bearing upon the investigator's ability to achieve a consistent quality of the photographic image if sources are obtained from separate depositories. Digital photography offers another alternative with the advantage that the digital image may be downloaded direct to a laptop computer and the computer generated reproduction of the original observed directly while the original is at hand. This allows the investigator to satisfy himself/herself that the reproduced image fulfils the required parameters before he/she leaves the depository. The resolution of the photographic reproduction is dependent upon film speed ASA/ISO or pixel array density (film and digital cameras respectively), lighting conditions (e.g. brightness and contrast) and ensuring the rigidity of the camera during exposure. Photography also introduces lens aberrations similar to those highlighted for photocopying. One advantage over photocopying is that the investigator has greater control over the selection of lens used. For example certain quality lens manufacturers publish distortion criteria for their lenses which, if deemed significant to the accuracy of the analysis, may be corrected by the application of a suitable computer-based algorithm to the digital image.

Copyright

Certain graphical historical sources of information may be protected by copyright. In certain instances copyright may restrict the ability of the investigator to obtain or reproduce information. For example, the Ordnance Survey impose a 50 year copyright rule governing reproduction of their map sheets. If the sheet required is no longer published and, as such, cannot be purchased in original format but falls within the 50 year copyright restriction, under normal circumstances the investigator may photocopy no more than 10% of the original (Ordnance Survey, Pers. Comm.). In these instances the investigator may wish to apply for permission from the Ordnance Survey to reproduce material or decide to simply trace the desired river channel features or undertake another form of analysis (e.g. direct measurement from the original). Matters of copyright may seem somewhat trivial in academic led non-commercial research into historical river channel change, but may typically take on a higher priority in applied studies. In some instances a depository may have a pre-existing licence to use particular material. For example, the 'Survey' Section at the Environment Agency, Thames Region, is licensed to use contemporary Ordnance Survey Sheets held in digital format.

Cost

Cost has typically been overlooked in academic studies of river channel change. If a pragmatic approach is taken to applied river channel change investigations then cost may have important implications which may determine what information is obtained and, therefore, the overall accuracy of the approach. Certain historical sources of information may not lie within the public domain and obtaining copies may only be possible at cost for commercial research. The same information may be offered relatively freely for academic-based research. Applied studies, particularly where the work may be conducted under contract must ascertain costs involved in obtaining material, issues of licence (e.g. for re-sale of information extrapolated from these sources) and of copyright. The same is true for software products used in the collection, manipulation and analysis of historical information. Such costs must be budgeted in the project design and may result in historical information sources perceived as non-essential being omitted from the investigation.

3.4.2 Information handling and manipulation

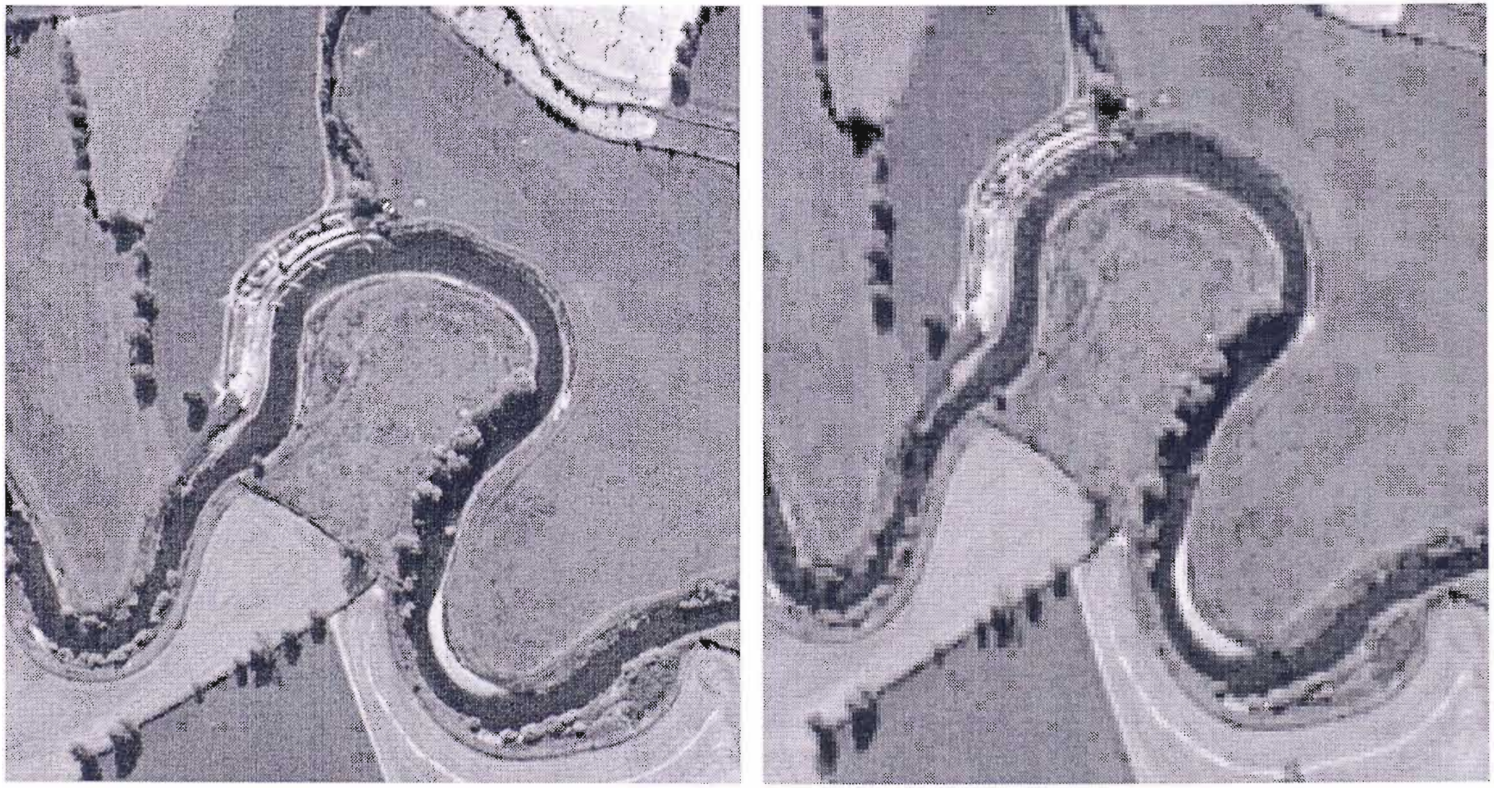
Prior to analysis of information for the extrapolation of river channel change information it is often necessary to manipulate the information into a form that allows a particular method of analysis to be conducted. Operational errors arise from the process of handling information because the manipulation of information involves the transcription of information. The specific nature of information manipulation and, therefore, the potential for error is dependent on the nature of the analysis deemed appropriate.

Reference indices

Extrapolating river channel change information from historical sources may be purely qualitative and based on the association between the representation of historical information at different moments in time. In these cases there may be no strict requirement to 'measure' in the statistical sense in order to make comparison. However the greater the degree of quantification required the greater the requirement for the investigator to standardise measurements to allow comparison. This may be referred to as the 'index' of comparison, akin to the notion of Degrees of Freedom outlined in Chapter 2 (e.g. Hey, 1978).

There is no strict requirement for the investigator to compare like sources of information (e.g. maps with maps, cross-sections with cross-sections) in order to provide standardised indices for comparison. However, as errors are considered to be scale dependent, the selection of the index used must be based upon common scales of representation. If two historical sources are compared to determine river channel change the Total Error will never be better than that of the historical source of information with the greatest inherent limitation.

The selection of a common datum is dependent upon the inherent characteristics of the historical source material. Section 3.2.2 observes that in some cases this decision has already been taken. Where the historical source material is not explicit in the representation of the datum this decision must be taken by the investigator. It is common that for a given size of fluvial feature, the greater the spatial resolution of the historical source of information, the greater the spatial options regarding the placement of the datum. For example, Figure 3.3 represents an image of a river channel represented in an aerial photograph. Representing the photograph at different resolution allows closer definition of detail at the river channel bank margin. The location of, for example, channel bankfull width or the bankfull



High spatial resolution

Low spatial resolution

Figure 3.3 Aerial photograph representation of the river channel at two levels of spatial resolution
The higher spatial resolution image allows more precise definition of river channel features

channel margin may be placed with greater accuracy (and by implication precision) at the higher resolution.

In practice there will be a limit to the resolution to which an image of the river channel may be enlarged. In the case of aerial images this is defined by the grain size of photographic film or pixel array density in a digital camera or video image and the contrast of the image.

There may be practical difficulties in the extrapolation of an index value. For example, if the investigator is attempting to define a banktop boundary from an aerial photograph the appearance of the river channel bank may be partially (or totally) obscured by vegetation. Plate 3.1 shows one such example for the River Hogsmill. Here the view of the channel is totally obscured from the air and determination of bankside features is difficult even from a ground-based within-channel viewpoint. Seasonal adjustments in vegetative cover may mean that the discrimination of channel indices is less certain in months where there may be greater vegetation cover. The water stage in the channel may also be significant, particularly where the flow depths are high and may obscure within-channel features.

The representation of the river channel may not necessarily be normal to the axis of the extrapolated measurement. For example, an oblique ground-based photograph taken from the channel bank looking down-channel will provide the investigator with a greater impression of channel cross-sectional characteristics than those of planform. The accuracy with which measurements of cross-sectional features may be extrapolated (e.g. estimates of channel bankfull width) is therefore greater than those of planform (e.g. estimates of reach length).

Plate 3.1 Vegetation obscured photographic image of the River Hogsmill

River channel features are obscured from aerial view and partially obscured from a ground -based perspective

Computer-based warping techniques may provide a degree of compensation for oblique angled imagery. This usually involves the placement of 'control values' within the image and effectively 'stretching' the image. The greater the displacement angle through which the image is warped the greater the loss of feature definition in the resulting image. As such, there is be a trade off between compensation for distortion and loss of image definition. Similar warping techniques described in Chapter 4 for planimetric topographic information involve only minor distortion of the image. The degree of image distortion from 'true' (as defined by the control values - themselves not error free) may provide an indication of potential error (see Chapter 4).

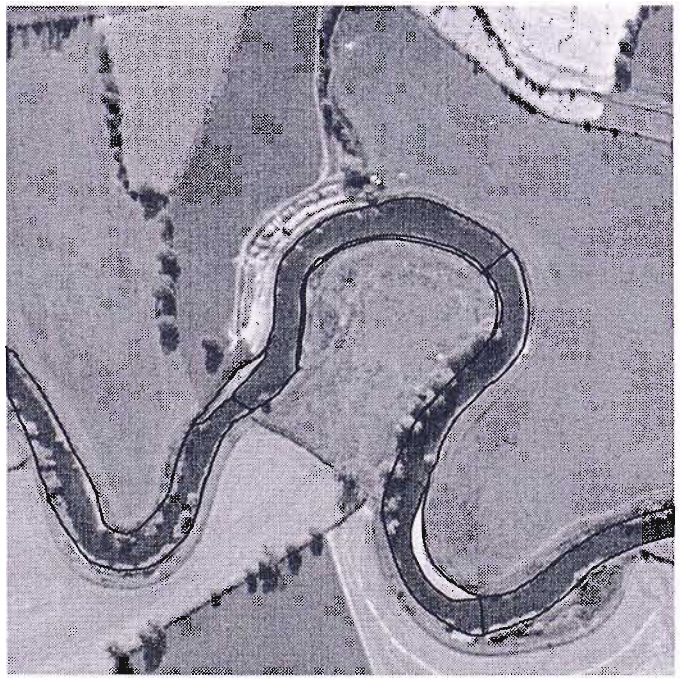
Topographic information is often provided without supporting sedimentary or vegetation information. In these cases the datum value must be made solely upon the basis of channel geometry. For example, in the case of channel cross-section information the channel bankfull width may be estimated on the basis of the relationship between the channel banks and the immediate floodplain surface level (Leopold *et al*, 1964; Woodyer, 1968; Harvey, 1969; Riley, 1972) or on the basis of the relationship between width and depth (e.g. Wolman, 1955). One such example, the Riley Bench Index (Riley, 1972) is described in detail in Chapter 5 for consideration of the bankfull measurement from historical cross-sections.

A final alternative to digitising as a means of datum definition is to automate the process within the computer itself (Hooper, 1992). Several software packages will allow the digital image to be modified in such a way that river channel boundaries may be recorded by association between the features in an image. Feature recognition involves instructing the computer to define features given a set of specific parameters. These may be associated with shape, hue, texture, intensity etc. Such methods are akin to supervised classifications used in remote sensing to define land cover classes. However, in dealing with retrospective historical information the investigator does not have the facility to ground-truth observations.

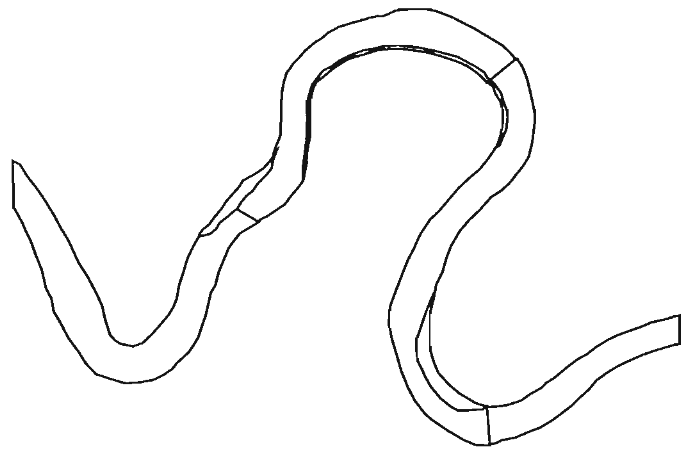
Information Transfer

Certain analysis techniques will require the conversion of information prior to analysis into a format that allows comparison. Graphical sources of information create the greatest challenge, particularly where computer-based techniques may be used to conduct the analysis. Computer-based techniques require that information is stored and manipulated in a digital format. Conversion of graphical information to a digital form will, without exception, involve a loss of information. Information loss results from the generalisation of information in digital format. Further conversion may also be required by the computational analysis to convert between digital data formats (e.g. raster to vector and vice versa). Systematic errors are incorporated at every phase of data transcription. For example, digitising has been used as a method for converting map information into a digital format. Burrough (1986) states that errors resulting from the digitising process are generated from the investigator's inability to perceive and digitise representations of objects. Instrumental errors are associated with the limiting precision associated with a particular method of digitising technique. A particular method of digitising will therefore have instrumental limits to the resolution with which features may be represented digitally. However, it is uncommon to have a digitising system that has an operating precision less than the digitising precision of the operator. Systematic errors occur as a consequence of the digitising method and (as before-mentioned) the spatial resolution of the features being transcribed. Take for example a meander arc; by digitising the meander arc is represented as a sequence of nodal points connected by lines. The meander arc is now represented as a sequence of straight lines which may be 'smoothed' by applying a computer algorithm; either way there is a loss of information between the model of reality represented in the original and the model now represented in the computer. Add to these the potential instrumental errors arising from the digitising equipment and the digitising method (e.g., 'line streaming' or discrete point capture) and human errors (mistakes which may go unnoticed) and the total error introduced at this stage of the operation is increased further. Repeat digitising of the same channel feature from the original may allow a mean value to be taken. However, this will still not overcome the positional errors associated with the computer-based representation but merely provide a reduction in 'peak' error (e.g. maximum deviation of the digitised line from 'true'). However, the derivation of the standard error of these values provides an indication of the degree of variance.

There are alternatives to conventional digitising that may minimise the errors that occur with 'cursor on paper' digitising methods as a means of information input to a computer-based format. Scanning or digital photography, for example allow the impression of the historical information to be represented on-screen, and digitising conducted on-screen. This allows for the investigator to magnify or reduce the computer-based image representing the river channel. This techniques provides the investigator with a greater degree of flexibility over the digitising procedure, particularly as attention is focused solely on the on-screen representation and not divided between screen and digitising tablet (Figure 3.4) In addition, the investigator may manipulate the on-screen image to highlight desired river channel features to be digitised (Figure 3.5).

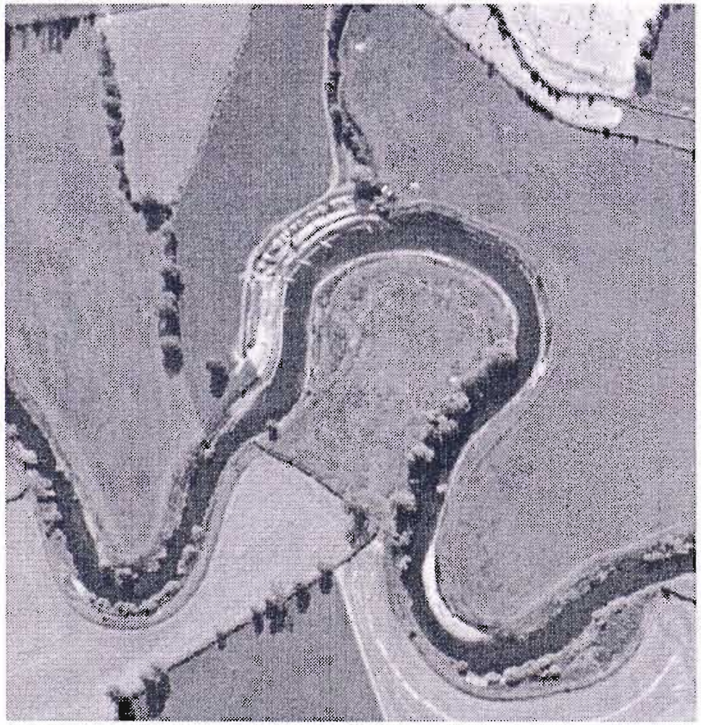


Selected river channel boundaries and features may be digitised on-screen

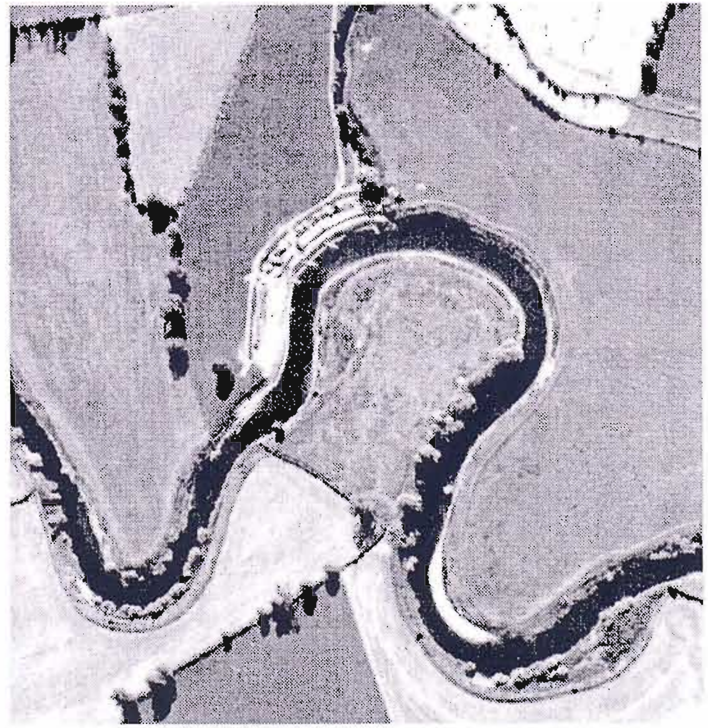


A vector respresentation of the selected river channel boundary locations

Figure 3.4 On-screen digitising of river channel features and boundary locations



Normal scanned representation of a river channel from an aerial photograph



Contrast enhanced representation to highlight sedimentary features

Figure 3.5 Image manipulation to enhance the representation of desired river channel features

The example demonstrates one such technique which has applied a contrast stretch to the black and white aerial photographic image.

Digital conversion of information from vector format to raster format involves further generalisation of information. The level of generalisation is dependant on the nature of the transformation. For example, a raster or cellular conversion will involve the investigator making a decision as to the size of the individual cell size (if information is held in a 'quadtree' structure this may be referred to as the 'Quadree Level'). Each cell may then have a certain attribute or attributes attached which may be nominal, ordinal or ratio. Individual cells do not therefore contain errors due to their location (which is fixed and referenced as absolute space but rather, contain errors due to the attribute information that is assigned to them). For example, for planimetric representations of the river channel, cells which lie close to the channel boundary have a greater opportunity for misrepresentation as, say, channel or non-channel, than cells further away from this boundary. Therefore, the greater the magnitude of channel change that occurs between temporally successive representations the lesser the likelihood that these misrepresentation errors will lie at the same location (Newcomer and Szajgin, 1984; Walsh *et al.*, 1984).

3.4.3 Information analysis

The analysis of historical information may take many different forms. The nature of the analysis is governed by the nature of the enquiry and the available information sources. Estimates of river channel change may be qualitative, quantitative or a measure of both and draw on single or multiple sources of information.

The most common form of analysis is based on comparison. Comparison may take many forms, most likely to be like format with like format but this is not exclusive. For example, estimating river channel change may be based on multiple format historical information and this does not exclusively mean that maps must be compared with maps, cross-sections with cross-sections (and so forth). A watercourse may have been recorded by many differing formats of historical information - in planform (e.g. maps) cross-section (e.g. engineers' plans) and the investigator may also discover historical drawings (possibly pre-dating the planform information) and/ or written information. Clearly there is likely to be considerable variability in the resolution of these different sources of information. For example, while channel bankfull width may possibly be estimated from the historical drawings it would be unrealistic to make a quantitative comparison between these and the estimates of bankfull width derived from engineers' cross-sections. The investigator may choose simply to extrapolate river channel change in a purely qualitative manner, expressing change in dimensionless terms such as 'enlargement' or 'reduction'. Alternatively the analysis may be two-tiered, treating both sources of information independently and quantifying only those values estimated from the sequence of engineering cross-sections.

3.5 THE PROPAGATION OF ERRORS

3.5.1 Derivation of Total Error

Error propagation analysis is the process of tracing the components of inherent and operational error from information capture to final estimate of change and attempting to determine the nature of the magnitude and direction of these errors and their significance. If the estimated value may be predicted as an absolute value or a relative value. For example, as a relative probability of the 'true' value this will provide a basis for providing absolute and relative measures of error with varying degrees of confidence (Chrisman, 1982). This will allow the investigator to assess whether the estimate of river channel change is true or a product of the propagated error.

Errors can never be erased from historical sources of information. Each historical record contains inherent error (as discussed). Operational errors are introduced as soon as the investigator proceeds to utilise this information to extrapolate river channel change information.

Total Error is considered to be a function of the component inherent and operational errors such that the estimate of river channel change will always be an approximation of the 'true' value (Muller, 1987; Lodwick, 1989; Chrisman, 1982),

$$\text{Total Error} = (I1 \;.\; I2 \;.\; I3 \ldots In) + (O1 \;.\; O2 \;.\; O3 \ldots On)$$

Where,

I = Component of inherent error

O = Component of operational error

This is based on the assumption that inherent and operational errors are independent. However, there is indeterminacy in the nature of the component errors. This is particularly the case for inherent errors where, in the absence of corroborating information, it may be impossible to derive a quantitative estimate of individual component error. For example, it is unlikely that the investigator will be able to determine the specific nature of survey errors in a map; instrumental errors in the survey equipment, systematic errors on the part of the surveyor in the depiction of river channel features and the possibility for the inclusion of gross error in the surveyed representation. The resulting depiction of the river channel, while a faithful reproduction of the survey information will propagate these errors to the cartographic representation. At best the investigator may 'infer' such errors from surrogate information. Two examples of surrogate information are identified in the following sections.

3.5.2 Temporal corroboration

Corroborating information requires the existence of two or more representations of the same river channel feature being recorded independently. The sources of information need not be recorded at exactly the same time:

a) Two records may be deemed sufficiently close in time as to represent near identical temporal conditions (e.g. with minimal anticipated change between the two representations). For example, the presence of a mill represented in a painting may be corroborated from written records, or from map evidence. However, it is possible that the two sources of information may be contradictory, in which case further information (or rejection of one or both of the contradictory sources) may be required.

b) Successive historical records may depict uni-directional change in a river channel characteristic. A singular historical record that defies this trend may be investigated more thoroughly before acceptance or rejection from the analysis. In this way sequential corroboration provides a means of evaluating a historical source of information. This assumption is based on the premise that there is continuity of change between the historical records (Lawler, 1993). This cannot be taken for granted and, therefore, the ability for successive sources of information for corroboration is highly dependent on the period between the information sources and the anticipated nature of river channel change.

c) It may be possible to corroborate historical information with contemporary field information, e.g. sedimentary analysis, dendrochronology etc.

3.5.3 Spatial association

Few historical sources of information are recorded solely and specifically for the purpose of extrapolating river channel changes. As such they may contain additional information which will allow the investigator to assess the spatial association between information contained in the same image. The most common form of spatial association is that of comparing the location of features within the historical representation for which there is assumed to be zero movement with features which may change. For example, two maps depicting the river channel may also depict buildings, road intersections etc. which can be assumed stationary for the period over which river channel change is estimated. If the investigator is able to estimate the relative 'change' in location between these features (e.g. distance, area, bearing etc.) this may provide a surrogate for estimating total inherent error between the two maps. However, this method will not provide an estimate of the error in any one individual map but rather the inherent error 'difference' between the two. This is because it cannot be assumed that the two maps contain the same degree of inherent error. For example, Hooke and Perry (1976) compared 23 Tithe Survey maps in Devon with 1st Edition Ordnance Survey sheets for the same area and record a relative differential error of 2.7% for lines and 3.94% for area. However, locations that are assumed to be fixed in the landscape - 'control points' - do allow the investigator to define an absolute measure of spatial error where these features may be assigned a location in space relative to a fixed datum (e.g. longitude and latitude, Ordnance Survey National Grid co-ordinates). In this case the comparison is made between values recorded on the map sheet and values assigned to the control points. Of course, the estimate of control point values is itself subject to error. If for example the control point values are themselves obtained from a map sheet (usually a contemporary sheet) the planimetric error so defined by the comparison still remains that of the inherent difference between the two map sheets. The assumption is typically made that the control point values are 'true' and thus any error in position is attributed to the (assumed) inferior map sheet. Alternatively, control point values may be obtained through contemporary survey (e.g. EDM, differential Global Positioning System (GPS)-based survey etc.) and as such will still contain surveying errors. However, in this case the investigator is better placed to estimate the nature and magnitude of these survey errors.

Errors estimated by spatial association are dependant on the system by which the estimate is made. As several control points are commonly used the 'residual' error between individual 'true' values and displacement values may be expressed statistically (mean, maximum and standard deviation). Residual values may also give an indication of the spatial variability of error across the representation. For example, a photocopied image will usually show greater spatial error at the margins of the image than in the centre as a consequence of photocopier lens errors. It is helpful therefore that control point values are selected, where possible, across the image and are not clustered. Computer based techniques may allow correction (termed 'rectification') of the digital representation of the river channel. An example is included in the analysis of planform information in Chapter 4.

3.6 SUMMARY

Errors limit the ability of the historical sources of information to interpolate river channel change. Understanding the limitations of errors allows the investigator to select information that is appropriate to the nature of the river channel investigation.

Total Error is composed of component inherent and operational errors which are propagated from the moment of collection to the interpretation of the results of the analysis. The significance of these component errors may be estimated. In certain cases, surrogate values may be chosen to represent them and used to attach relative and absolute estimates of error to river channel change estimates.

CHAPTER 4

A GIS-BASED METHODOLOGY FOR EXTRAPOLATING RIVER CHANNEL PLANFORM CHANGE: RIVER TOWY, DYFED.

4.1 INTRODUCTION

This chapter will present a methodology for extrapolating river channel planform change using a Geographic Information System (GIS)-based approach. The methodology provides a means of quantifying the nature of lateral adjustment of river channel planform based on the representation of river planform features in maps and aerial photographs. The basis for comparing representation of river planform features is not new (e.g. Lawler (1993) provides one such review) and river channel planform methods have been extensively reviewed in the academic literature (e.g. Hooke, 1984). The emergence of GIS-based techniques for spatial information handling and analysis from the mid 1980's provides the river channel manager with the opportunity to apply these methods to the extrapolation of historical river channel changes. The method outlined in this chapter allows the investigator to estimate the historical stability of selected reaches of known length and proposes the 'Historical Stability Index' as a means of classifying a reach on the basis of its lateral stability over the period of historical analysis.

Such indices may only prove helpful to aiding river channel management decisions where the lateral adjustments may be validated for the period of study. The GIS-based methodology proposed in this chapter provides the investigation with a means of estimating the probable magnitude of component inherent and operational errors.

Analysis of the propagation of these component errors allows for the estimation of Total Error (see Chapter 3) which allows the significance of observed channel planform changes to be set against information loss and error generated by the method.

The aim of this investigation is to develop and test the effectiveness of the GIS-based methodology to discern indices of river channel planform change and not specifically to provide a detailed examination of river channel planform change for the test river channel. These methods have been developed and tested for the River Towy, Dyfed.

The implications of the methodology for interpreting river channel planform change may be assessed in terms of their application to other river channels in England and Wales. If values for Total Error may be estimated for a given set of conditions then the limitations arising from the technique may then be used to determine the methods effectiveness with smaller and/or laterally-inactive rivers.

As such, the specific objectives of this chapter are as follows:

a) Introduction to the River Towy study site and the suitability of the river as a test-bed for the GIS-based methodology.

b) The presentation of a GIS-based methodology for estimating river channel planform change.

c) Assessment of the errors and limitations of the methodology.

d) Assessment of the implications of the results of the methodology for understanding their application to other river channels.

4.2 THE RIVER TOWY STUDY SITE

4.2.1 Study river requirements

In attempting to develop a GIS-based technique for extrapolating river channel planform change the chosen study river was to fit the following requirements:

a) A river that had already demonstrated a history of river channel change through lateral adjustment well documented in previous academic and management-based studies.

b) A river which exhibited differing magnitudes of planform adjustment in space and time.

c) A river for which there was a comprehensive and easily accessible record of historical sources of planform information.

Through discussion with Prof. John Lewin (University of Aberystwyth) regarding previous studies conducted for Welsh gravel bed rivers the River Towy, Dyfed, was chosen as best fulfilling the above criteria. Furthermore, through information obtained at the University of Aberystwyth it was possible to contact and discuss the characteristics of channel behaviour first hand with academics and river channel managers who had studied and/or have managed the River Towy.

4.2.2 A background to the River Towy

The River Towy, Dyfed, south-central Wales flows from head-waters dammed by the Llyn Brianne reservoir 19 Km north of Llandovery south-west to Carmarthen. (Figure 4.1). As suggested, background information concerning the River Towy, in particular its geomorphological characteristics, is readily available through the assessment of academic literature, geomorphological management-based reports and through personal discussion with academics and river channel managers familiar with the watercourse. In particular, Smith's research published in 1987 and 1989 provided the most comprehensive coverage of the geomorphological characteristics of the River Towy watercourse and proposed a coarse stability classification based on river channel planform adjustment. A review of these sources is provided in Table 4.1and illustrated graphically in Figure 4.2.

The River Towy is Britain's 19th river on the basis of catchment size and length, (1092km^2 and 82km respectively, Ward, 1981). The River Towy drains a structurally concordant valley and main features were formed in the Tertiary (Brown, 1960). Valley gradients are typically high. Valley widths are highly variable depending on local valley confinement which may be disproportional to down-valley distance. For example valley widths are approximately 1500m at Llandovery yet approximately 500m where locally confined at Llandilo further downstream.

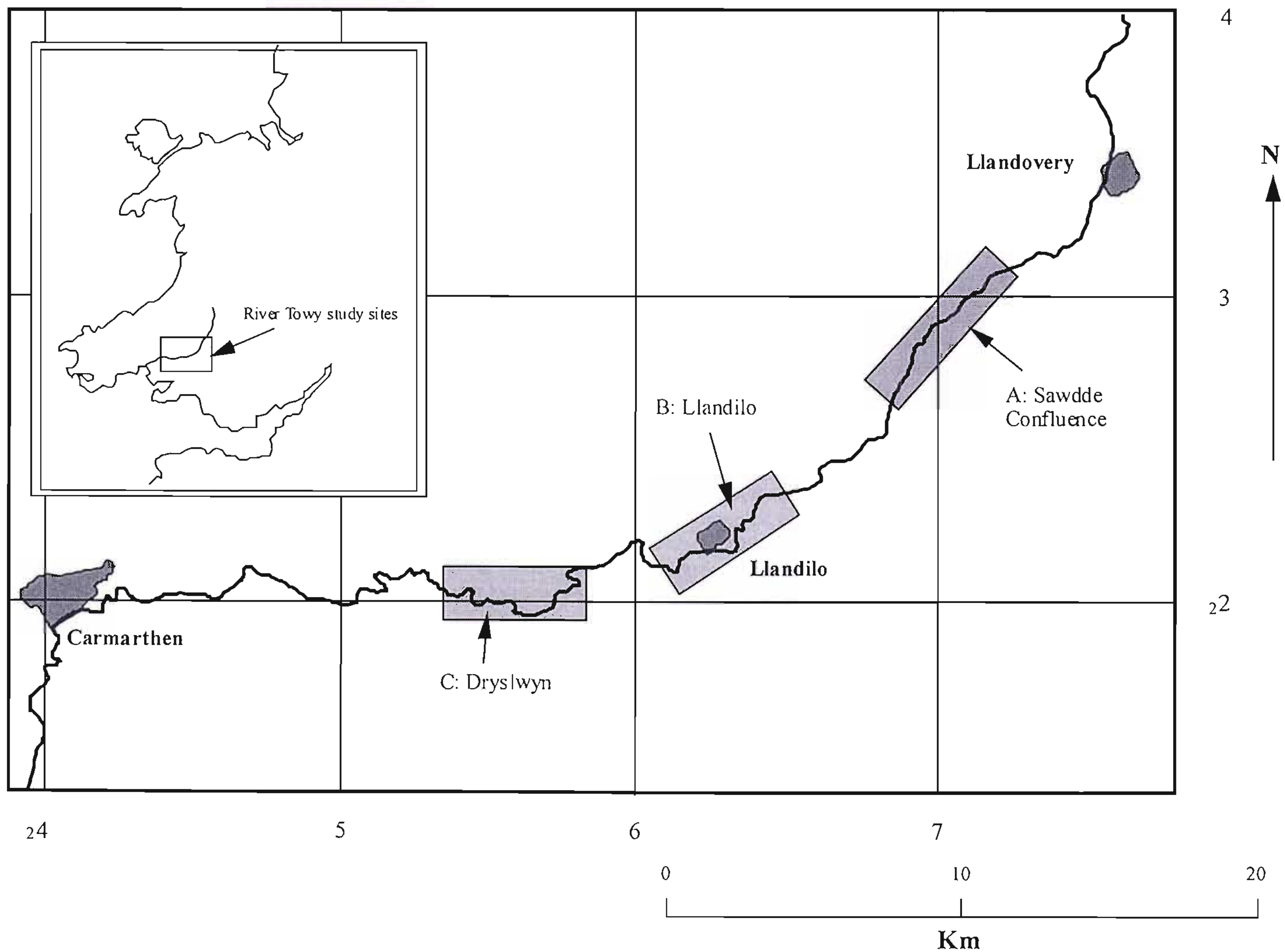


Figure 4.1 River Towy study sites

Lewin & Manton, 1975.	Two river bends near Llandovery and Llandilo were considered. Air photo interpretation from a 1971 survey clearly identified relict meander loops on the Towy floodplain. Comparison of documented historical records dating to the mid 19th century period demonstrated reaches immediately downstream of Llandilo have been stable for over 130 years.
Lewin & Brindle, 1977.	Channel confinement by the Carmarthen railway line presented. Six types of documented historical source were considered from the mid 19th century to a 1971 Air Photo survey. River channel path length and sinuosity were calculated at each date. The conclusion from this research was that meander loop development resulting from channel confinement has involved the formation of a deep scour pool and an unstable channel reach adjacent to the embankment.
Blacknell, 1982.	Within this study a minor aspect was the consideration of a loop development at the Dryslwyn site. The only conclusion drawn was that the loop had developed since 1946.
Lewis & Lewin, 1983.	14 Welsh rivers were investigated to identify and explain cutoffs. Of the rivers investigated, the Towy demonstrated the greatest number of cutoffs (19). These 19 cutoffs were located in the area subsequently chosen for pilot study sites. Historical sources used in the study ranged from the mid 19th century Tithe surveys to the 1971 Air Photo survey.
Lewin, 1984.	This study was prepared as a report for the Welsh Water Authority (WWA) which investigated river channel stability along the Towy. The study noted that the Towy has demonstrated persistently high erosion rates for over a century and on the basis of this past behaviour, the river channel's sinuosity may be expected to increase for many years. This study was the first of the academic studies to consider management of the river. In terms of the management options available for controlling the planform adjustments, Lewin concludes that, "Short of lining the channel continuously it would be difficult to stabilize this reach of the Towy effectively."
Newson & Leeks, 1986.	This technical report to the WWA examined the geomorphological effects of gravel extraction sites on the Towy. Newson and Leeks consider that commercial extraction has been problematic causing the disruption of the sediment continuity resulting in channel degradation, but the severity of these effects is masked by the influence of flooding.
Lewin & Chisholm, 1986.	This study was complementary to that of Newson and Leeks (1986). It investigated the historical channel developments at the gravel extraction sites at Llwynjack and Llanwrda. Eight sources of documented historical evidence were investigated, from the first series OS sheets at 1:10 560 scale in 1884. They observed that some reaches demonstrated high rates of mobility for short periods (e.g., a 1947 snow-melt flood) and that the most recent period (to 1986) shows the greatest degree of movement.
Smith, 1986.	This PhD thesis is concerned largely with the Towy and its morphology and sediments. It is possibly the most comprehensive of the historical studies conducted to date on the Towy, and it provides much detailed contextual information for the present study.
Smith, 1987.	Reflects the research undertaken on the Towy for the PhD on the nature and morphology of counterpoint bars.
Smith, 1989.	The river channel between Llandovery and Landilo is subdivided into 3 categories: Stable, Active meandering and wandering. He states that active segments of about 1 Km are interspersed with inactive segments of about 1.5 km.
H.M.S.O., 1990.	In this Government report on the collapse of the Glanrhyd Saeson railway bridge on the 19th October 1987, hydrological considerations are noted but the study fails to recognise the geomorphological development of the river channel. Details are provided of the nature of bridge scour and flood events on the 18th and 19th October 1987.

Table 4.1 Previous academic and management-based studies on the River Towy (see also Figure 4.2)

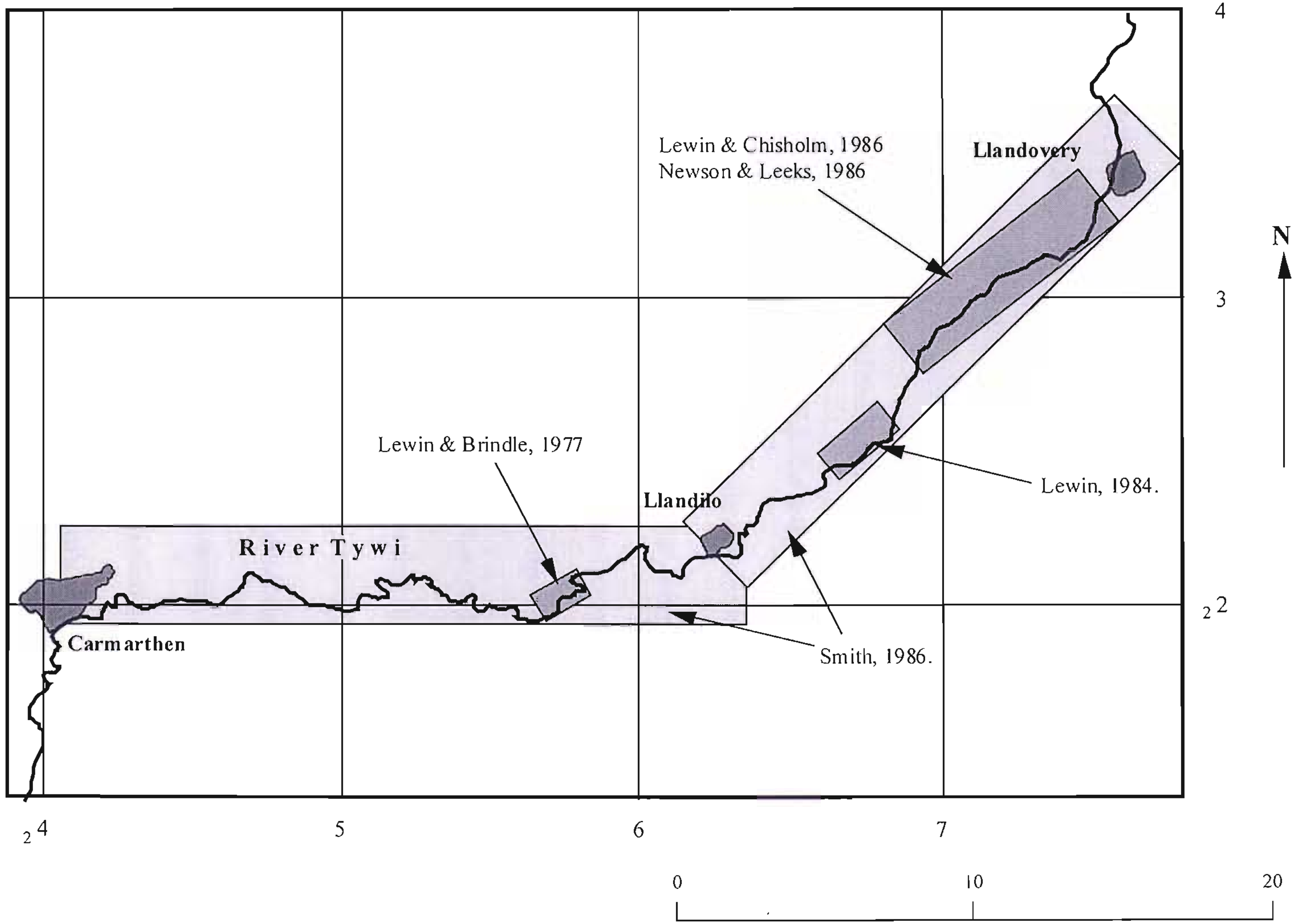


Figure 4.2 The location of previous academic studies on the River Towy (see also Table 4.1)

Prior to the construction of the Llyn Brianne reservoir in 1972 the flow regime of the River Towy was unregulated. However, despite flow regulation from the dam the River Towy is still subject to bankfull floods two or three times a year (Smith, 1986), although Lewin (1984) notes that there has been a reduction in the frequency of overbank flows. The River Towy has a mean annual discharge of $38m^3.s^{-1}$ at Ty Castell (SN 491204) with the largest recorded discharge, with an estimated return period of 100 years, of $1270m^3.s^{-1}$ in 1931 (Smith, 1986).

The post Tertiary development of the River Towy valley has undergone a variety of human-induced land-use changes. With the settlement of the first farmers in south Wales approximately 5000 years B.P the valley underwent wide-spread deforestation for arable farming, sustained up to the 19th century when permanent grassland had replaced arable farming (Davis, 1938). Land-use change has increased the amount of sediment delivered to the river and resulted in floodplain aggradation throughout the late Quaternary (Smith, 1986). An examination of the floodplain stratigraphy at Dryslwyn (SN 553200) by Blacknell (1982) revealed floodplain sediments consisting of sandy-gravels comprising >60 % gravel and >10 % sand. These large accumulations of gravel have periodically been exploited through commercial extraction. Gravel extraction has continued to provide a primary industry on the River Towy, such that in 1988 there were 14 licensed gravel extraction sites (Newson and Leeks, 1988). Lewin and Chisholm's report to the Welsh Water Authority (1986) notes that gravel areas appear to be more extensive in earlier surveys. Where this gravel has been over-extracted this has impacted upon the river channel's stability. The migratory movements of the river and the aggradation of gravels, which may take many years to establish to agricultural grade land, has resulted in a net loss of agricultural land to the river within the 150 year period of the historical record investigated (Lewin, 1984).

A further major influence in the geomorphological development of the River Towy in the last 150 years has been the construction of two railway lines in the mid 19th Century linking Llandovery to Llandilo and Llandilo to Carmarthen (Figure 4.3). The single track Llandovery to Llandilo line was opened in 1858 and remains in service. An incident on this line on 19th October 1987 as a result of the river bridge collapse at Glanrhyd Saeson claimed the lives of 4 people. The bridge collapsed as the direct result of scour at the base of the foundations induced by flood flows and drew direct attention to the significance of developing a geomorphological appreciation of river channel change (HMSO, 1990). The collapsed bridge was replaced and the line re-opened in 1988. The Llandilo to Carmarthen line was open between 1864 and closed in the mid 1960's (Carmarthen Public Records Office). The track has now been removed on this old line, but the railway embankment still remains in a variable state of repair.

The construction of the two railway lines had, and continues to influence the behavioural adjustment of the River Towy. The construction of the railway embankments, standing up to approximately 5m above the level of the valley floor, affected the river directly through both localised re-alignment of the river channel and extraction of gravels from the valley used in the construction of the embankment. The impact of late 19th century railway construction upon river channel change in England and Wales has not been exhaustively studied. Certainly river channel re-alignment has had the effect of promoting accelerated instability, particularly through meander confinement (e.g. Lewin and Brindle, 1977). The

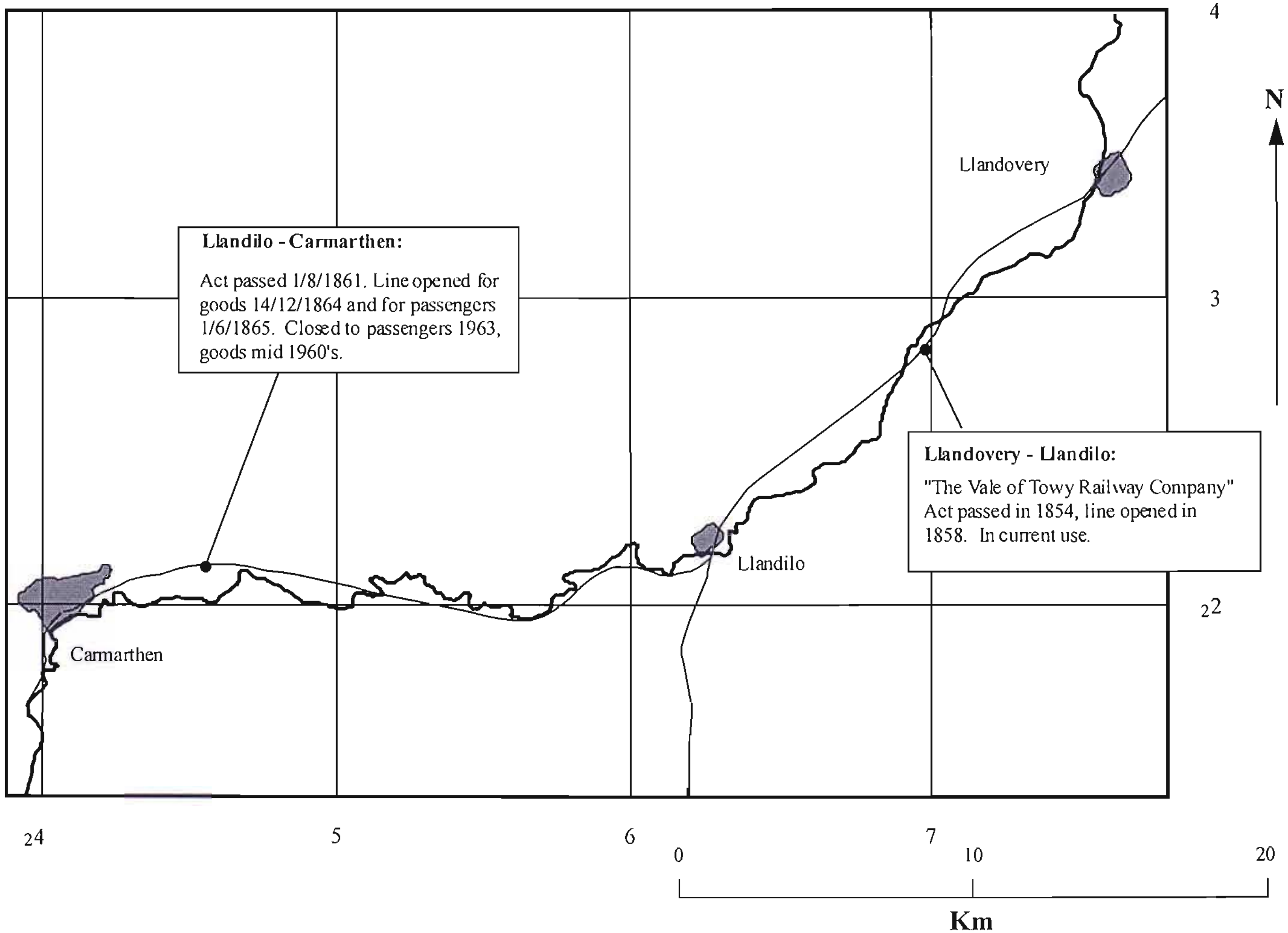


Figure 4.3 The location of the railway lines

affect of the removal of large quantities of gravel used in the construction of the embankment has been noted but in less spatially specific terms. The embankments also serve locally to reduce the effective floodplain size leading to modified flow and sediment exchanges between river and floodplain with modified flow velocities and depths. Concern that the railway embankments may be breached by the migrating river has prompted action to strengthen the embankments (including those of the disused line) at specific sites. The consequence of breaching the embankment would be potentially disastrous in terms of re-routing the flow of the channel for extended sections.

Present day management by the Environment Agency (formerly the National Rivers Authority at the time of this investigation) has been in response to the fluvial adjustment of the River Towy. This has been through isolated bank protection at specific sites to attempt to mitigate against excessive lateral erosion, regrading of the Sawdde tributary with a series of shallow weirs and flood embanking immediately upstream of Carmarthen. Details of recent management activities were discussed with Mr. Owen, of the National Rivers Authority (NRA) Carmarthen area office in 1993 and presented in Table 4.2 and Figure 4.4.

4.2.3 Study sites on the River Towy

Given that the aim of this investigation was to develop and test a methodology for assessing the nature and magnitude of historical river channel change and not specifically to determine the underlying geomorphological causes promoting these changes, it was decided that the investigation should focus upon specific study sites rather than adopt a catchment wide analysis. Such an approach is helpful in this

Reference	NGR	Date	Operation
A	415195	1970 & 1984	Carmarthen flood protection Scheme.
B	494203	1969	Weir installed for gauging, no longer used. Since instalment island forms which is periodically removed.
C	548200	1984	Beili-glas Farm: 2000 Tonnes of stone on erosional bank. This had to be put back in place in 1987 following movement d/s.
	578203	1986	Pant-glas: The Towy was practically through the old railway embankment at three points. The embankment was rebuilt with shoal material.
D	577209	1981	Ro-Fawr: Path adjacent the river bank had to be moved every year. In 1981 the channel was stone lined. A cut-off developed following the storm of 1987, this was blocked at the upstream end with local shoal material as gradient perceived as problematic at Pant-glas.
E	615213	1989	Welsh Water Sewage treatment works: Erosion of bank, WW paid £ 50K for boulder armouring of the bank.
F	640230	No date given	Ty-gwyn Farm: Gas line across the channel was removed due to channel migration. A new line and bouldered groyne at the gas works site.
G	688288	1987	Glanhyrd Saeson, rail bridge collapse following the flood of Oct 18/19th October. New bridge subsequently constructed.
H	695282	1986	Sawdde confluence: Channel straightened + weirs. Immediately d/s of confluence island development >1986 at 693278.
I	718311	1987	Towy broke into the Dulais tributary. Old tributary course now forms flood channel.
J	725317	1989	Towy cut into the Mynys channel widening it from 3ft to 30 ft - formed the new channel of the Towy to old confluence point.
K	750330		Periodic shoal removal at railway bridge.
L	757340	No date given	Channel migration at rugby grounds - stone groynes.
M	762354	No date given	Tonn confluence: Erosion and shoal development, shoal removal and stone embanking.

Table 4.2 Recent management of the River Towy (see also Figure 4.4)

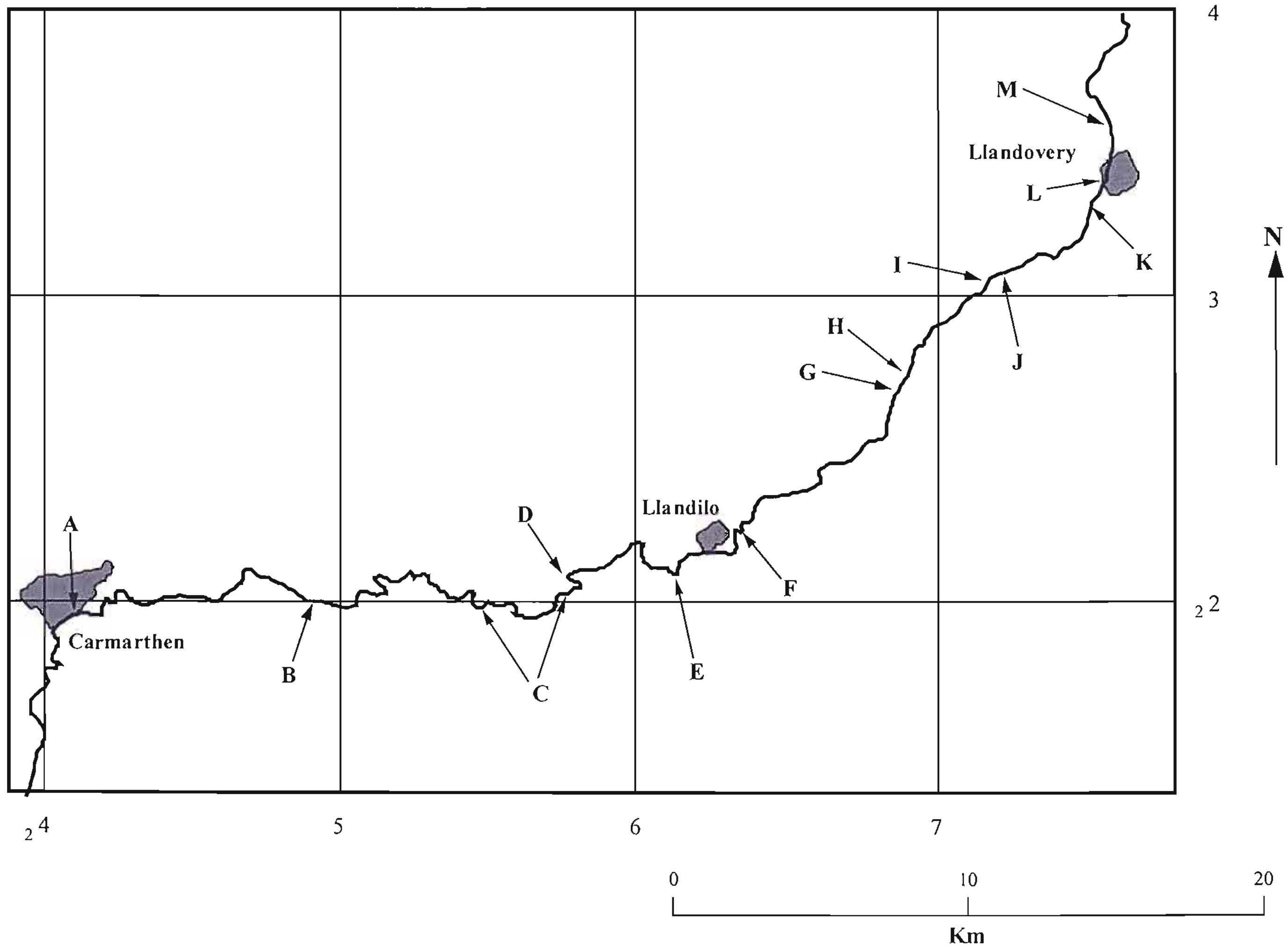


Figure 4.4 Location of recent management examples on the River Towy (seeTable 4.2 for detail)

context because it allows for the selection of sites with proven (from previous literature) but differing rates of adjustment and differing physical size. However, approaches are limited where the geomorphologist attemps to determine process-based cause effect relationships; while the localised site-specific changes may be attributed in part to local conditions they make no reference to flow and sediment continuity through the watercourse as a whole. For this reason, were the approach to be adopted for the purpose of determining a fuller appreciation of geomorphological evolution it is recommended that a more catchment wide approach (at least investigating reaches immediately upstream of chosen study reaches) be adopted.

Prior to final selection the sites were visited a geomorphological reconnaissance survey conducted to confirm the expectations of the academic and management-based literature. This survey was conducted in May 1992 on foot and by boat (certain areas could not be readily accessed by land) between Llandovery and Carmarthen. On this basis three sites were chosen for detailed investigation, each of approximately 5km reach length. The locations of the three study sites are shown in Figure 4.1 and their characteristics are provided below:

Site A: Sawdde confluence

The site is of interest as it lies directly downstream of a major gravel extraction site, and includes the confluence with the Sawdde tributary (SN 694280) noted in Best (1986). The Sawdde itself has been identified as a channel which has exhibited widespread planform adjustment. In 1987 it was channelised with boulder walls on both banks extending upstream from the confluence. In addition, river channel managers confirmed that the site was also subject to changes in slope characteristics believed to be a consequence of gravel extraction. Localised channel scour is believed responsible for the failure of the railway bridge at Glanhyrd Saeson at the north-eastern limit of this site. Furthermore, the lower course of the Sawdde has been regraded with a series of shallow stone weirs locally to reduce stream power and reduce headward erosion (see Plate 4.1)

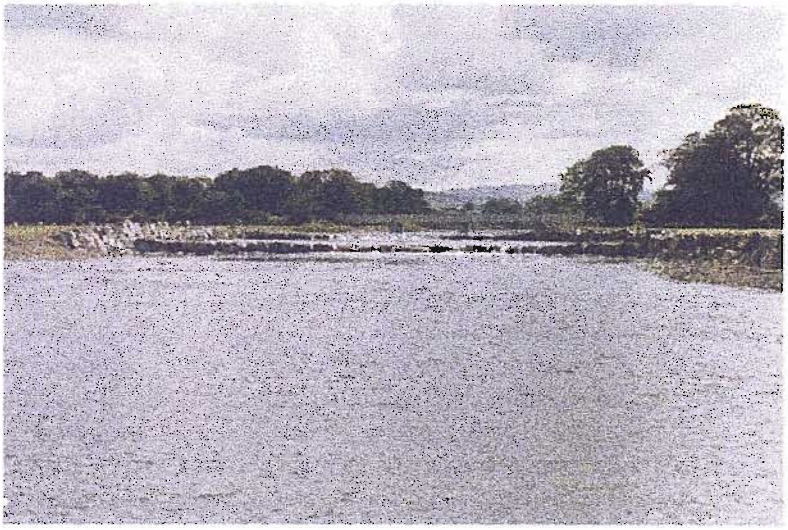
Site B: Llandilo

This site includes the confluence of the tributary of the Afon Dulais (SN 647240). The channel is naturally confined by the valley to about 500m at Llandilo Bridge and also by the railway embankment at Llandilo. Construction of the railway embankment at Llandilo in the late 19th Century was responsible for localised re-alignment of the river channel. Re-alignment at this site resulted in the net loss of channel length, increasing slope and promoting accelerated lateral change. Given the degree of natural confinement it is assumed that hitherto relatively stable reaches have become unstable. Consequently, the site includes two reaches that have undergone recent extensive channel modification to protect banks from further erosion; at Ty-Gwyn farm (SN 640230) where a gas-line crosses the river, and, at the Welsh Water Authority sewage treatment works (SN 640230). The latter example is illustrated in Plate 4.2.

Site C: Dryslwyn Castle

A feature of this site is meander confinement to the south resulting from the disused railway embankment. While the railway is no longer used for rail transport the embankment remains and continues to exert an influence upon channel development

Prior to modification, March 1987



Immediately after modification, July 1987

Plate 4.1 Channel modification at the Sawdde confluence Site A, summer 1987

Prior to modification, winter 1988/9

Immediately after modification, summer 1989

Plate 4.2 Channel modification at Welsh Water STW Site B, summer 1989

Plate 4.3 The railway embankment at Ro-Fawr , Site C

Localised meander confinement against boulder protection at the toe of the embankment. Railway dates from 1865, boulder bank modification from 1981.

through localised confinement. This site includes the area studied by Lewin and Brindle (1977). Channel working at this site includes the construction of a boulder wall at the site of Ro-Fawr (SN 548200) adjacent to the railway embankment to mitigate further channel migration (see Plate 4.3).

4.3 A GEOGRAPHIC INFORMATION SYSTEMS (GIS) METHOD FOR IDENTIFYING AND QUANTIFYING RIVER CHANNEL PLANFORM CHANGE

4.3.1 Methods in the study of river channel planform change

The study of river planform change from historical records is the most extensively researched means of determining historical river channel change. Methods used in this study have tended to be driven by available technology and research paradigms in geomorphology such that qualitative assessments tended to give way to semi-quantified manual comparison (e.g. overlay), digital analysis (e.g. Spectral Analysis) in the early 1970's, and the emergence of GIS-based techniques at the close of the 1980's. The 1990's has a seen a consolidation of the use of GIS-based techniques, digital imaging, and virtual mapping. Each successive advance in technology seems to have been applied to river channel change analysis. But there are risks:

a) There is the possibility that, in the absence of checks and control regarding information quality and suitability, the results of the analysis may be highly quantified and visually impressive, but weak because of insufficient consideration to inherent and operational errors.

b) The research is driven by the technique and does not necessarily challenge new geomorphological thought. As Braben (1985) observes,

"Research driven by technique .... seems to be a poor bet, since almost invariably the technician's skill is a solution looking for a problem." (p.401).

c) There may be a tendency to over-complicate questions that may require relatively simple answers. In particular, applied geomorphological research must seek solutions to provide answers via the most efficient route and not necessarily the most technologically impressive. Efficiency is as much about communication as it is about discovery.

The GIS-based methodology outlined in this chapter for extrapolating river planform information is one of many GIS-based techniques that may be utilised by the geomorphologist to promote an understanding of river channel change. The methodology is not considered unique: the technique draws on cartographic and geomorpholgical principles that were defined well before the method's formulation. Similar methods have been employed for the study of volumetric change (e.g. Milne and Sear, 1996) and in a range of geomorphological environments. Also, it is not considered that the method necessarily be adopted in a stand-alone capacity; the example provided in Chapter 7 illustrates that its value to applied geomorphological research is greatest where adopted as a component of the geomorphological analysis and there will remain areas of the historical investigation for which there is no substitute for field based survey. In this respect the application of GIS-based analysis is seen very much as a tool at the geomorphologist's disposal and not a means to discovery in itself. GIS-based techniques may allow the geomorphologist to manipulate and analyse different formats of information that was hitherto impossible to such a degree of precision, but that does not necessarily imply an increase in analytical accuracy.

The methodology presented here then illustrates one such use of this technology, particularly, in that it demonstrates how the available historical information may be optimised to produce results which may be set against an understanding of their error content. The technique has several advantages over (for example) manual methods:

a) Digitising of boundaries of interest from source documents allows ease of data storage, error checking, update and retrieval.

b) Spatial rectification methods can be employed to correct planimetric errors in the original source documents.

c) Attribute data can be linked interactively to map data.

d) The user can undertake spatial queries and analysis of area. For example, area analysis can be undertaken on individual records or historical sequences of records.

e) Digital statistical outputs provide savings in time as data may be exported directly from the GIS into, for example, statistical analysis software.

f) A variety of map products can be produced and refined until they represent the patterns of interest in the most effective way and aid the communication of results.

The results of the River Towy test will therefore demonstrate the utility of the technique for a range of differing river channel environments with a range of river channel planform information.

4.3.2 Historical river channel planform information for the River Towy

Historical river channel planform information is interpolated from the representation of river planform from maps and aerial photographs. The individual sources of historical information used in this study are shown in Table 4.3. Additional information used to corroborate information interpolated from these sources is ascertained from a geomorphological reconnaissance survey conducted in 1992 and a qualitative assessment of oblique, ground-based photographs for isolated reaches of the three study sites provided by the Environment Agency (formerly National Rivers Authority).

4.3.3 Information Collection

Information was collected from four principle depositories. Maps were viewed at the British Library (London), National Library of Wales (Aberystwyth) and Carmarthen Public Records Office; Aerial photographs were viewed at the Aerial Photography Section at the Welsh Office (Cardiff). There was near duplication of maps chosen for this analysis at all three depositories. Original copies of all maps

Survey Date	Source	Scale	Site Coverage
1839-1848	Parish Tithe Maps	Various scales	A, B & C
1861	Vale of Towy Railway Map	No information	A (Partial)
1884-1885	1st Series OS	1:10560	A, B & C
1904-1905	2nd Series OS	1:10560	A, B & C
1946-1948	RAF AP	1:10000	A, B & C
1947-1952	Provisional Series OS	1: 10560	A, B & C
1965	OS AP	1:10000	A
1971	Fairey's Commercial AP	1:7500	A, B & C
1975	Cartographic Services AP	1:10000	A, B & C
1975-1986	OS Metric series	1:10000	A, B & C
1985	J. Storey Commercial AP	1:20000	A, B & C

OS Ordnance Survey
AP Aerial photography

Table 4.3 Historical sources of information used in the investigation of planform change

(with the exception of the Tithe Survey Sheets) may have been purchased directly in original format from the Ordnance Survey. This was not deemed necessary; firstly because the methodology was specifically attempting to examine the nature of inherent error through obtaining photocopied and traced representations of originals, and, secondly because the 'original' would itself be a photographic reprint from an original plate.

Later Ordnance Survey sheets were traced from original format with ink onto plastic film as these sheets could not be photocopied in their entirety due to restrictions of copyright (they were less than 50 years old) and prohibitive costs of purchasing original sheets. With the exception of the Tithe Survey sheets, all maps were reproduced at their original scale of 10:10560 and 10:000 scale. The same original survey information is available at 1:2500 scale from the same depositories. While it is accepted that reproduction of sheets at this original scale would allow much closer recognition of river channel boundary condition (especially when tracing from and original and digitising) these were not chosen. As before-mentioned, the purpose of the test was to assess the nature of errors and not necessarily seek (in this case) to minimise them.

All aerial photographs were traced from original prints. Attempts to photocopy these using a standard black and white photocopier were rejected on the grounds that the photocopied image had much reduced levels of contrast and definition. Using ink and plastic film the river channel boundary was traced for the 'overlap' location of spatially successive stereo-pairs of photographs. Choice of the location of the river channel boundary attempted to record the level of the 'banktop' condition, or the 'normal winter level' as recorded for the Ordnance Survey Sheets with which the aerial photographs would be compared. In practice, the definition of this boundary proved more subjective in certain cases that others such that the perceptual error meant that the planimetric error in boundary placement varied across the photograph. Corroboration with field-based survey revealed that:

a) Eroding channel boundaries characterised by sudden breaks of slope allow the boundary to be placed with precision. For example, a bank which may be exhibiting cantilever type failure, when viewed aerially, is represented as a clear distinction between what may be regarded as 'channel' (water) and 'non-channel' (floodplain). Eroding channel boundaries which exhibit slump type failures still may be defined from the floodplain surface with moderate precision. Depositional channel boundaries, typically shallow gradient gravel bars proved the most unreliable boundary to define. The lack of a sharp break of slope between water surface and floodplain meant that there is the potential for perceptual error in placing this boundary.

b) Vegetation can both enhance and retard the ability to place the river channel boundary condition with precision. Vegetation succession across depositional bars proved helpful in defining the perceived 'active' limit of the gravel bar. This characteristic may be complicated in the case of scroll bars and mid-channel bars which may exhibit a differential degrees of succession. Mature overhanging vegetation would obscure the channel boundary. Isolated trees were not deemed problematic, however there are occasions where channel banks may be continuously tree lined. However, field evidence suggests that mature tree-lined channel conditions have a greater association with banks displaying minimal planform adjustment.

c) Aerial photographs were viewed and traced as stereo pairs, although (in this case) the resulting representations were not planimetrically corrected. Stereoscopic vision allowed the definition of the banktop condition to be recognised with greater confidence than when viewed from a single image. The ability to magnify the view of the image in the stereoscope allowed this boundary to be traced with greater precision.

In all cases where imagery was traced it was necessary to assign ground control points to each image to allow for image rectification following digitising of the representations. The digitising software allowed for up to 25 ground control points to be assigned per representation. In practice this was not possible in the case of the River Towy because there are extensive, relatively featureless, areas of rural floodplain with few locations that could confidently be assumed to occupy a continuous location. This was not so problematic with the tracing of maps because the sheet covered a relatively large ground area, but for aerial photographs represented at a higher spatial resolution the stereo overlap ground area between successive frames is relatively small. If fewer than six ground control points could be assigned to each tracing then control point locations would be sought outside of the stereo overlap area. Where possible control point values were chosen across the representation without clustering and close to the river channel boundary.

Control point values were obtained from the most recent metric Ordnance Survey Sheet at 1:10000 scale using a micrometer to obtain National Grid co-ordinate values. The digitising software demanded that Ordnance Survey National Grid co-ordinates used for control values be entered as 12 figure grid co-ordinates. This demands that control point values be defined to the nearest metre. The use of the micrometer and magnifying glass with a 1:10000 scale sheet allowed such definition and there was no perceived benefit of using 1:2500 scales sheets for this purpose.

4.3.4 Information handling

Information handling considers the operational stages required to manipulate the historical planform information into a format that suitable for analysis. This operation requires three stages; digitising, image rectification, and digital format transfer.

Digitising

Digitising refers to the process of transcribing information from a paper format to a digital computer-based format. For any one series of sheets (photocopies or ink on film tracing of originals) two methods of digitising are possible using a standard digitising tablet and cursor method:

a) Individual sheets comprising a section of each study site may be digitised individually. The complete digital representation of the study site can then be constructed within the GIS model by importing individual sections which have rectified and registered (geo-referenced) using the control point values to a common 'basemap'. The basemap represents a geo-referenced blank template onto which the individual sections may be registered.

b) Individual sheets comprising a section of the study site may be manually 'edge-matched' on the digitising tablet and the study site may be digitised in its entirety. The complete digital representation of the study site is then imported to the GIS as one complete file which has been rectified and registered.

Both of these methods have their advantages and disadvantages with regard to the preservation of planimetric accuracy. The first method allows for a greater density of control point values to be assigned per unit area of map sheet (the software allows a maximum of 25 control point values to be assigned per file). However, reproductive, digitising and rectification errors may result in line mismatches at the end of each digitised section. In the case of the River Towy this effect was found to be exaggerated where there were fewer control point values identified in the individual sections. However, attempts manually to edge match individual sheets proved problematic also, particularly for the representations obtained from aerial photographs due to scale distortions towards the edge of the image (this may have been reduced were images plotted stereoscopically). Given the length of reach being digitised, scale of representation on the sheets and size of the digitising tablet it was also impossible to represent the entire length of the individual study reaches. Instead a half-way solution was adopted whereby representations with low density ground control were manually edge-matched and digitised continuously and sheets with higher density ground control were digitised individually. The entire study reach is therefore temporarily transcribed as a series of individual sections (each an individual file) which may then be individually rectified in accordance to the ground control values assigned and then registered to a blank 'basemap'. Digital line mis-matches may then be corrected by attaching any remaining 'dangling nodes'. The resulting digital image is then saved as one file representing the complete study reach for the particular date of river channel representation. The process is repeated for every survey date in the historical record for each of the three study sites.

The manual digitising process itself was conducted by following the path of the river boundary location. It was discovered that it was preferential to subdivide the river channel into short reaches representing approximately 500 m in length when digitising defining the end of each digitised reach with a node point from which to start the next. This made the digitising process somewhat easier as gross errors detected whilst digitising could be corrected back to the nearest node rather than requiring the whole bank to be re-digitised. This also allowed for individual river channel features to be distinguished in the resulting digital model. For example, ox-bow lakes and cut-off points may be defined as individual digital units.

Digital Rectification

Digital rectification is the process of registering the digitised outline of the river channel features to the basemap and effectively warping the digital image with respect to the control point values. In theory the rectification process is improved the greater the number of control point values. However, clustering of control point values may result in preferential weighting being given to isolated control points. It must be remembered that the assignment of control point values themselves are prone to inherent and digitising error. Using the TYDAC product SPANS GIS the number of control point values is limited to 25 per file. SPANS GIS will estimate the Root Mean Square (RMS) error for each control point value. This value, otherwise called the 'residual' error value represents the distance that any one control point value lies from its 'true' designated location (in reality this 'true' value is limited in resolution to the nearest 1m and is itself dependent on the ability to distinguish features within this tolerance from the reference map). Residual values prove useful in three respects:

a) They allow the operator to identify gross digitiser errors (particularly in assigning control point values) because these individual residual values may be recognised as statistical outliers. These points may then be re-digitised or rejected from the analysis.

b) The frequency distribution of residual values provides an estimate of the mean, maximum and standard deviation of control point values for each individual file. This allows the investigator to assess the variability of planimetric error between files (and by implication between different historical sources of information). If these values are deemed to exceed a given level of tolerance the sheet may be re-digitised or rejected. Repeat digitising of the same sheet will indicate the nature of the digitising error (see Section 4.4.3).

c) The spatial distribution of residual values across individual files may be investigated.

Assignment of reaches

The methodology used in investigating specific locations within each of the three pilot study sites was to divide up each site into individual reaches. In this case 500m reach units were chosen to represent each reach. Because the start and end points of each reach cannot be assumed to remain stationary between surveys it is not appropriate to delimit reaches simply on the basis of channel extents. Instead, a series of landscape 'cells' are identified which are designated from the latest Ordnance Survey sheet. These cells are established with fixed boundaries which may be overlain onto any of the previous map editions to identify comparable reaches and so allow area analysis for the same geographical area to be undertaken. A consequence of this procedure means that as the river channel is migrating the river channel length between entering and exiting a cell will vary between dates of the historical record.

500m was used as the standard average length of channel from the latest OS sheet/s, but equally the chosen reach unit could have been 100m or 2 km and the choice here is purely representational. The reach polygon resolution depends largely on the requirements of the study. A lesser reach length introduces a greater spatial resolution in the channel change information and so decreases the extent to which the spatial patterns and trends are smoothed over the site. Logically, the appropriate reach length would be better related to reaches defined on the basis of the historical analysis and/or field evidence. For example, there is no necessity to have equal length reaches and reach statistics may be expressed in terms of average adjustment per metre.

Information format transfer

The final stage prior to river channel planform analysis using the GIS software involves the transfer of information into differing formats acceptable to the analysis procedures. At this stage the digital representation of the river channel represents simply the river channel boundary as a 'vector', lines constructed of individual 'arcs' connected by 'nodes' or end points. Analysis procedures may use these vector representations, but are limited as they do not define areas of space merely boundaries in space. Information format transfers within SPANS GIS involves the transcription of the vector river channel representation into polygon and raster formats:

a) A Vector to Polygon transformation converts boundary representations into closed polygons. Areas of the digital model, so assigned, may then be assigned attribute information. In this case the attributes attached define the polygon as 'river channel' and, for each individual date of the temporal sequence, the 'date' of the digital representation which referred to the aerial photograph date or map survey/revision date.

b) A polygon to map transformation converts the digital representation from polygon representation to a raster or cellular digital representation. The smallest unit of the raster representation is the grid cell. The spatial resolution of the grid cell may be defined by the conversion transformation. The choice of grid cell size has important implications for the accuracy of the analysis because the conversion involves the generalisation of information. In theory, if grid cells are chosen which are smaller than the planimetric error in the polygon representation (the degree to which the river channel boundary location lies from true) then these errors will not be magnified by the conversion process. As the size of the grid cell approaches the magnitude of the anticipated error, so the conversion process may mis-represent information leading to enhanced errors. The difficulty arises because the investigator may not be fully aware of the nature of the planimetric error at this stage. The residual values will provide an estimate of probable error at this stage, however:

- Planimetric error will vary across individual polygon representations such that mean distortion values may lie below a particular tolerance value, but peak distortion values will vary locally across the sheet.

- Raster overlay analysis techniques (described in Section 4.3.5) require that all files used in the analysis be represented at a common level of spatial resolution (a common cell size). Different files representing different dates from the historical record will have different residual error values depending on the variable nature of the inherent source material. As such, the choice of cell size must be with respect to the file with the minimum indicated residual error, even though the planimetric error of the resulting analysis will be no better than the historical source of information with the worse planimetric error.

In SPANS GIS grid cells are arranged in a 'quadtree' data structure such that spatial dimension of the grid cell is defined by the 'quadtree level'. The quadtree level defines the number of times the original basemap (the 'Universe') is divided four-fold. For example, a quadtree level of 1 represents 1 cell the same size as the universe, a quadtree level 2 has cells which are half of the size (a quarter of the area) of the universe, a quadtree level 3 has cells which are a quarter of the size of the universe (a sixteenth of the area), and so forth. All of the three pilot study reaches were located within the same universe.

As discussed in Chapter 3 for a raster representation there is no such thing as a spatial error because all grid cells are fixed with respect to the basemap or universe on which they are represented. Errors arise as a consequence of classification or the attribute values attached to each individual grid cell. In this example the attributes are carried over from the polygon classes from which the raster representation is constructed - cells are defined initially in a nominal format as 'channel' or 'non-channel'.

4.3.5 Information analysis

This section details three methods of historical analysis that were undertaken to extrapolate river channel planform change information; vector overlay, raster overlay and the estimation of a Historical Stability Index.

Vector overlays

Overlaying of vectors within a GIS may be thought of as a similar procedure to manually overlaying sheets of tracing paper. Vector representations of the river channel boundary may be displayed showing overlays of any number of dates from the historical record. Animation between successive records in the sequence provides a helpful visualisation tool for observing these changes. Displacements between records represents the net lateral extent of movement. These distances may be measured on-screen by dragging the cursor between points of enquiry. As the period of temporal separation between records is known it is, therefore, possible to estimate values of mean annual lateral displacement. Furthermore, the direction of movement may be observed (e.g. at a meander apex) allowing the investigator to establish the mode of meander adjustment, e.g. extension, translation, rotation etc. (Hooke, 1984).

Area Map Overlay

Area Map Overlay procedures utilise the raster representations of the river channel planform. Because each grid cell has a unique spatial location then comparison between dates is based on the nature of the attribute information attached to each grid cell. In this example grid cells are assigned a nominal attribute of either channel or non channel. As such the reclassified map so produced by comparison of any two maps from the historical record may be considered as a matrix of possible outcomes (Figure 4.5). Grid cells that changes from channel to non-channel are classified as an area of deposition, non-channel to channel as an area of erosion. Therefore, the resulting map so produced exhibits the planform extent of net erosion, deposition and no-change between the two dates.

This information may then be analysed in any number of ways in order to extrapolate quantitative values representing net changes in river channel planform location in space and time. In the case of the River Towy, each study site was divided into a series of spatially consecutive reaches of 500m length. As noted in the previous section the choice of reach length in this case was arbitrary for the purpose of exemplification and has no significance to reaches exhibiting geomorphologically homogenous characteristics. As the channel area is so defined for each reach then river channel planform change (erosion and deposition) may be expressed in absolute terms (e.g. $m^2.m^{-1}.a^{-1}$) for each reach. Comparisons may also be made expressed in relative terms (e.g. % erosion, % deposition) and/or consider the ratio

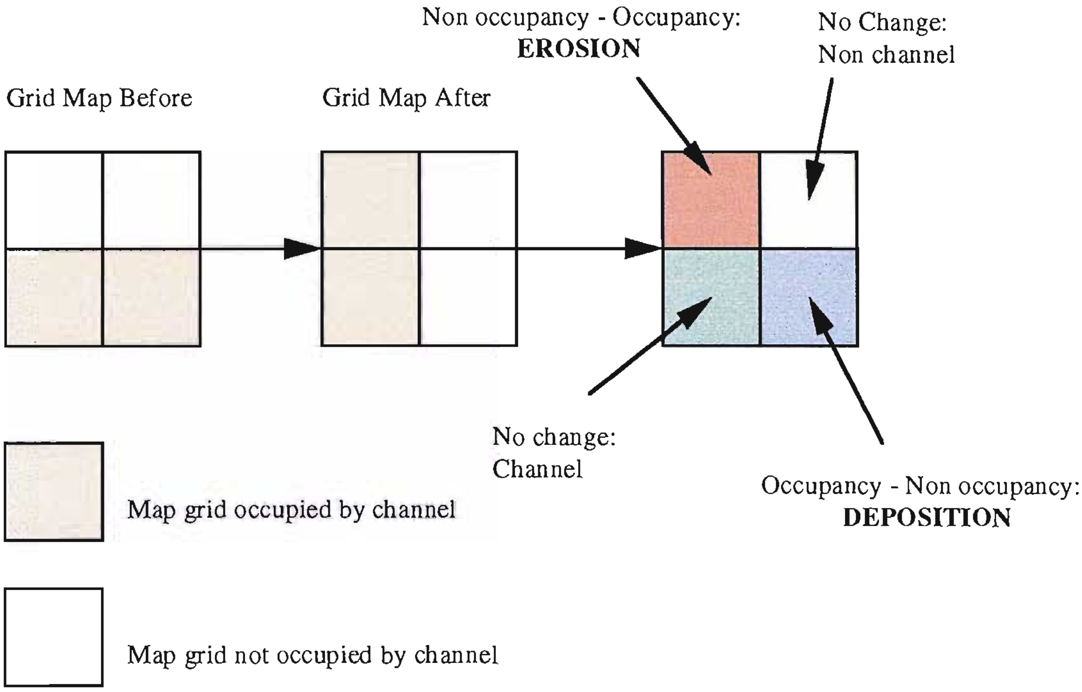


Figure 4.5 Area map overlay of any two raster-based planform representations

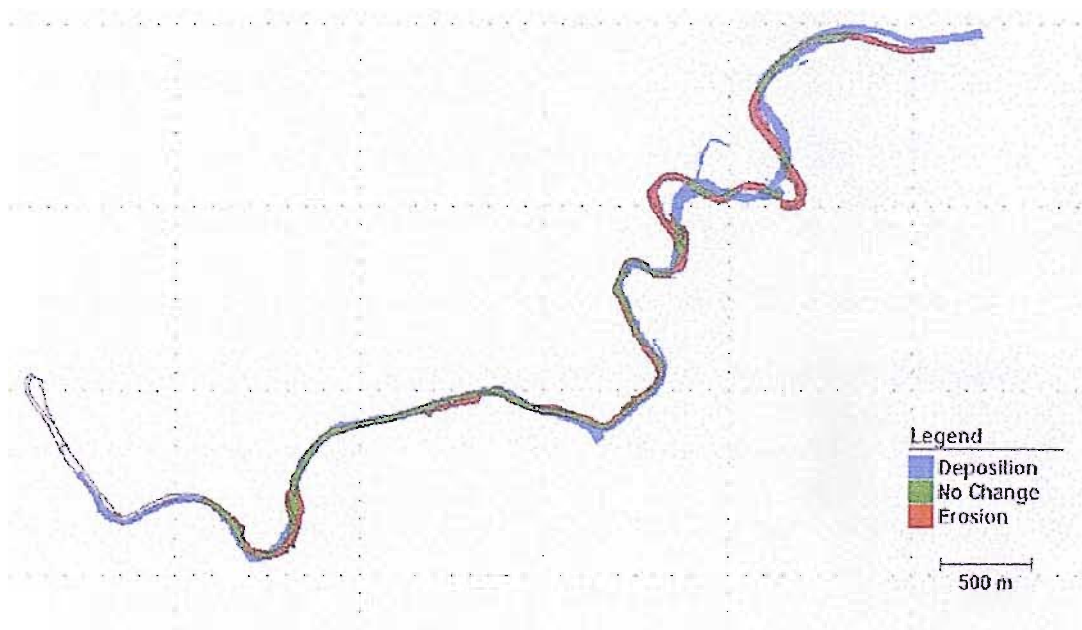


Figure 4.6 Example of area map overlay for Site B, 1947-1971

between erosion and deposition. Figure 4.6 illustrates an example for study site B for the River Towy.

Historical Stability Index

The previous method assumes a nominal classification for each individual historical record of channel and non-channel. Because the sequences of historical records are typically separated by unequal periods of time, attempts to overlay any more than two dates from the historical record at any one time are compounded. However, the attribute value assigned to each grid cell need not be nominal but assigned a value based on ordinal or ratio scales. Furthermore, any given grid cell may be assigned multiple attribute values.

In this example individual grid cells are weighted in terms of the number of years separating their survey date from the previous record (Figure 4.7). For example, if the separation of two planform records is 30 years then the grid cells representing channel occupancy (as defined by the planform boundary location) are assigned class attribute values of '30' to indicate that that particular grid cell is assumed to have been occupied for 30 years. The remaining grid cells are classed as '0' indicating continuous non-occupancy for 30 years. The procedure is repeated for the next map in the series, for example, if the period of time separating the two records is 15 years then cells are classified as '15' and '0', and so forth through the record. Overlaying all of the raster representations in the record produces a reclassified digital map - grid-cells are classified from '0' to '144' indicating that individual grid cells may have been occupied by river channel from zero to 144 years (the total period of the historical investigation).

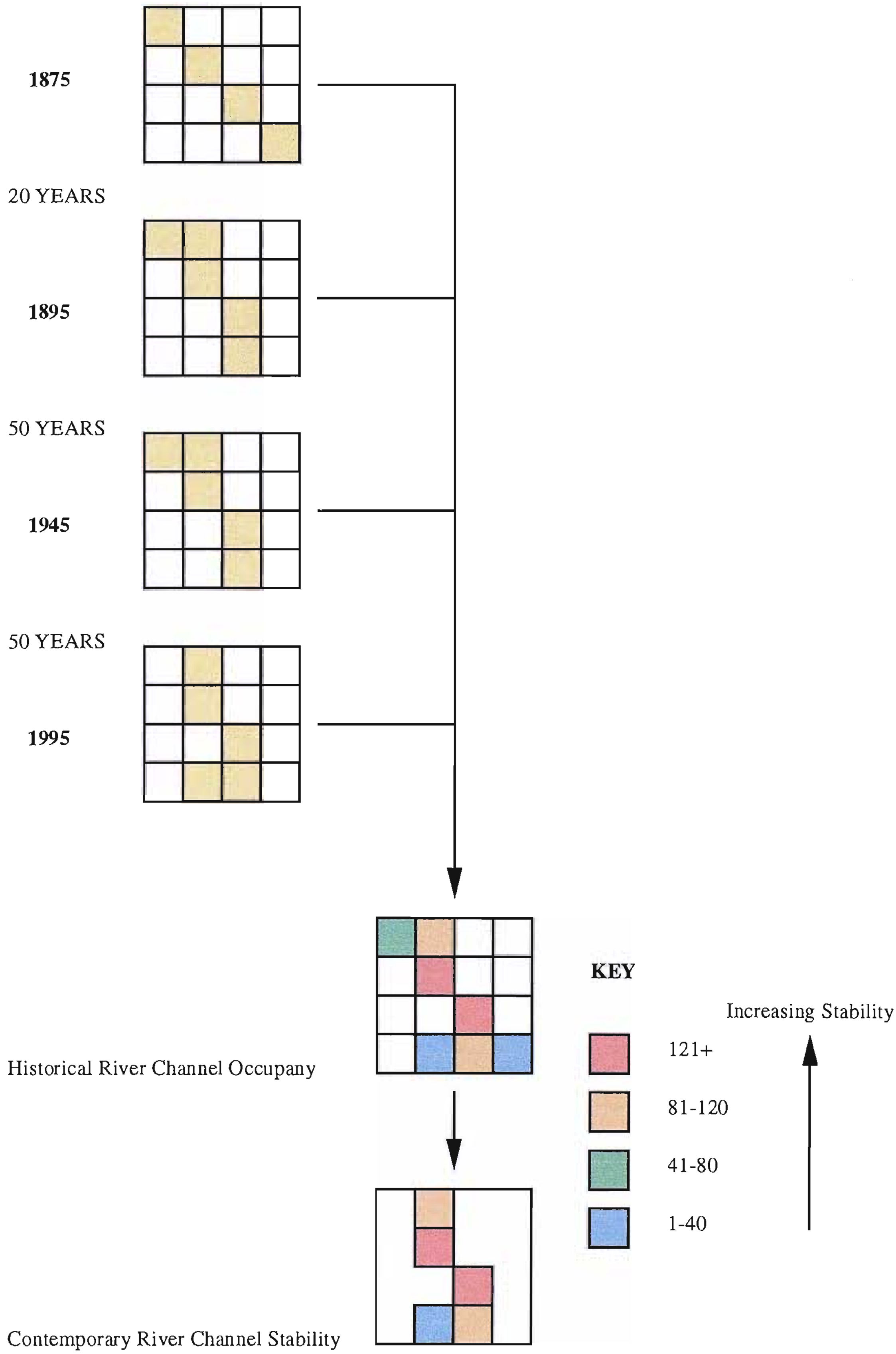


Figure 4.7 Historical stability index

Individual raster-based planform representation is weighted. Two products of the analysis indicate (i) Historical river channel occupancy - all pixels, (ii) Contemporary river channel stability - occupancy of last planform record in the sequence.

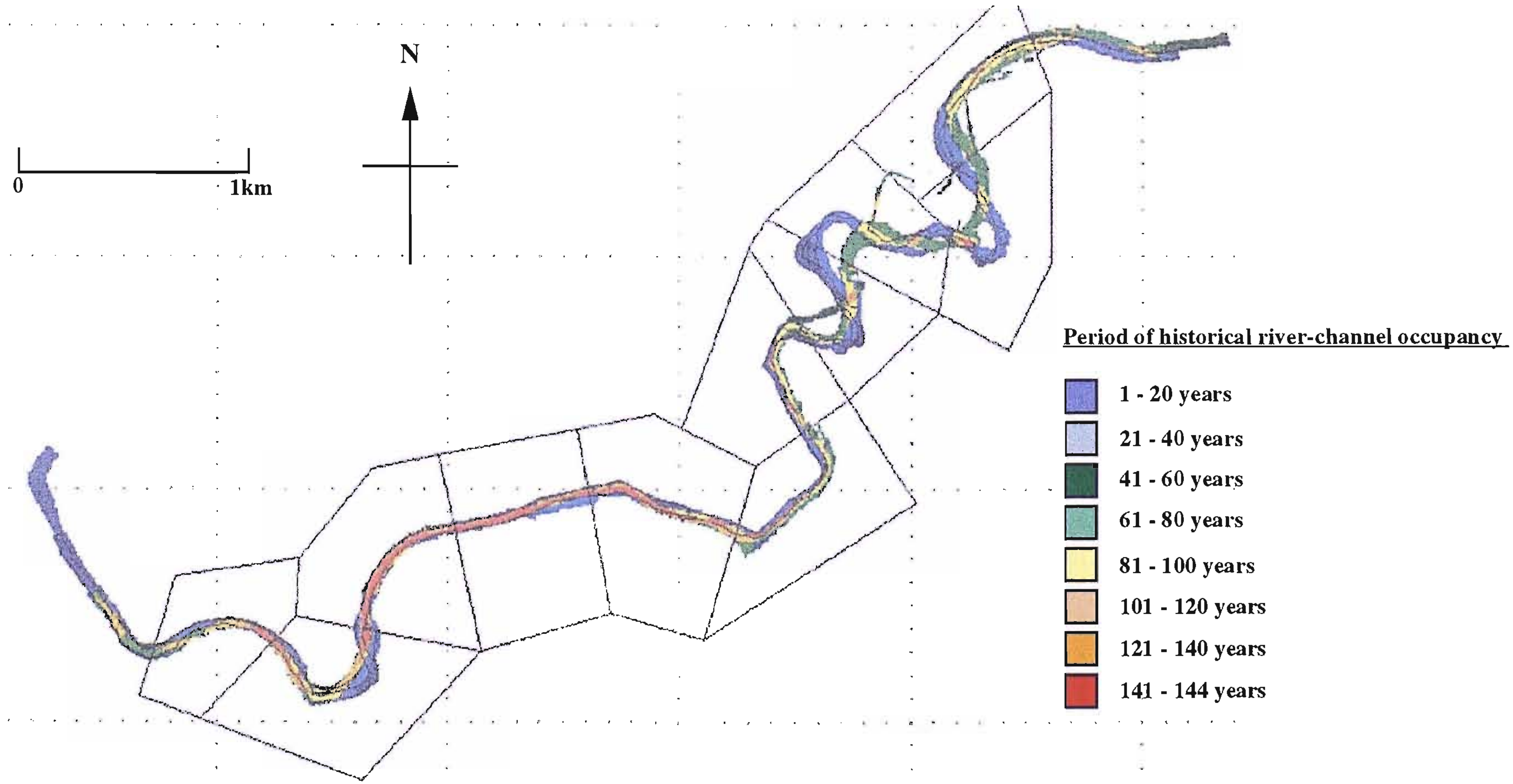


Figure 4.8 Historical stability index example to demonstrate the period of channel occupancy at Site B
Legend indicates the number of years over the 144 years of historical record that individual landscape units (as defined by the quadtee level) are occupied by 'active' river-channel. Landscape units which exhibit relatively high periods of total channel occupancy are deemed to be relatively stable based on available historical inforamtion. Reaches are defined at 500m intervals.

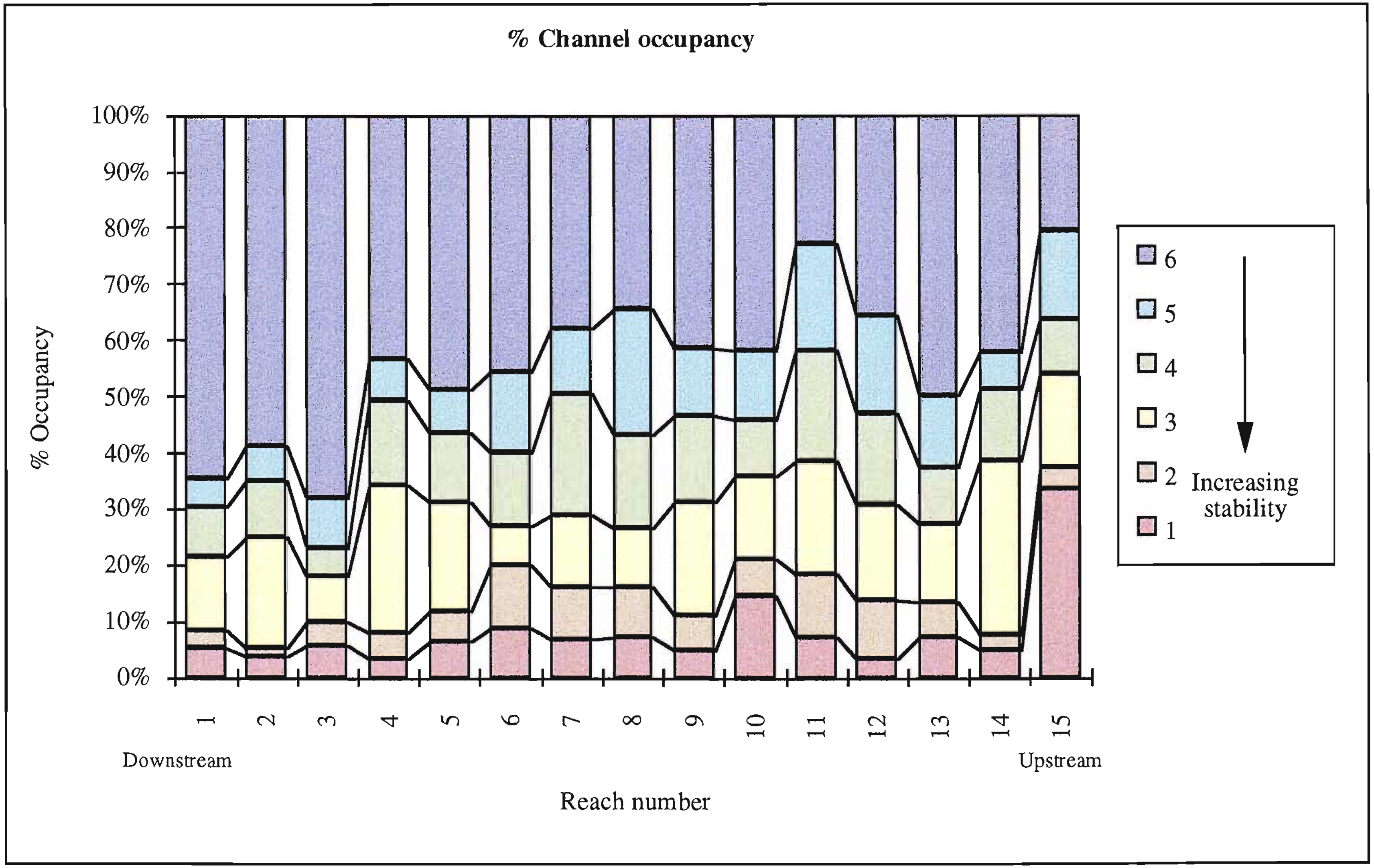


Figure 4.9 Historical stability index example by reach for the River Dee (Gurnell *et al.*, 1994)

When the final map was viewed a range of 144 colours proved somewhat difficult to visualise. Instead the map was reclassified into 20 year units of stability as follows:

Class 1 = > 140 years of channel occupancy

Class 2 = 120 - 139 years

Class 3 = 100 - 119 years

Class 4 = 80 - 99 years

Class 5 = 60 - 79 years

Class 6 = 40 - 59 years

Class 7 = 20 - 39 years

Class 8 = 0 - 19 years

If river channel stability is defined in absolute space the classes so defined by this procedure may be considered Stability Classes for the period of observation. In this example, Class 1 is the most stable, Class 8 the most unstable. Figure 4.8 illustrates an example for Site C on the River Towy.

Figure 4.7 demonstrates that the last record of the sequence may then be overlain as a vector outline onto the new map and was used as a template to cut away all of the map information beyond the boundary of the last record. The result is a map representing the river channel at the period of the last record that represents planform areas of variable occupancy throughout the period of the record.

As with the Area Map Overlay procedure, the study site may be divided into a series of reaches and class based statistics exported in order to quantify spatial trends in the information. This procedure was adopted by Gurnell *et al.*, (1994) for the analysis of historical planform change on the River Dee (Figure 4.9).

4.4 THE ACCURACY OF THE APPROACHES

4.4.1 Introduction

This section examines the specific nature by which errors are propagated through the analysis through an investigation of the nature and magnitude of the inherent and operational component errors.

4.4.2 Inherent errors

Inherent errors are those errors that exist in the river channel planform information prior to analysis. Two formats of historical information are used in the River Towy study, namely, maps and aerial photographs. Each format will have specific errors which may be considered format specific and there are errors which may be common to both of these sources of information. Inherent errors occur spatially as planimetric errors across the map and aerial photographs, or as temporal errors as a consequence of limiting information concerning the time of the original survey of map sheets.

In the absence of corroborating information it is impossible to estimate the exact magnitude of spatial error. However, using spatial association techniques highlighted in the previous chapter it is possible to provide a surrogate measure for estimating the magnitude of the inherent error. This was expressed through the analysis of the displacement of control point residual values from their 'true' location (Figure 4.10). Strictly speaking, the residual error of any one control point also incorporates the operational errors associated with precisely digitising the control point value. Therefore, the following assumptions are made:

a) 'True' values are estimated from the 1985 metric Ordnance Survey map. Values of the Northing and Eastings values of each control point are obtained with a micrometer. Measurements are obtained to the nearest metre on the ground, this implies a level of generalisation however, SPANS GIS will not accept control point values at any higher resolution such that the working precision by which control point values are obtained is assumed more accurate than the level of generalisation required by the GIS.

b) Cartographic errors in the 1985 Ordnance Survey map are assumed minimal. In reality the comparison the residual error estimate of control point values represents the 'difference' between the reference map (1985 sheet) and the map or aerial photograph being examined. Strictly speaking, comparisons of residual values between sheets are 'relative' to each other as obtained from the same reference map but absolute values do not necessarily represent the departure of any one control point value from reality. If greater spatial accuracy is required for the ground control point values they may be assigned by contemporary survey. In practice the precision to which control point values need be fixed is dependant on the nature of operational generalisation, resolution of inherent material, minimal required planform tolerance required of the analysis, and, size (and, by implication, cost) of the study area.

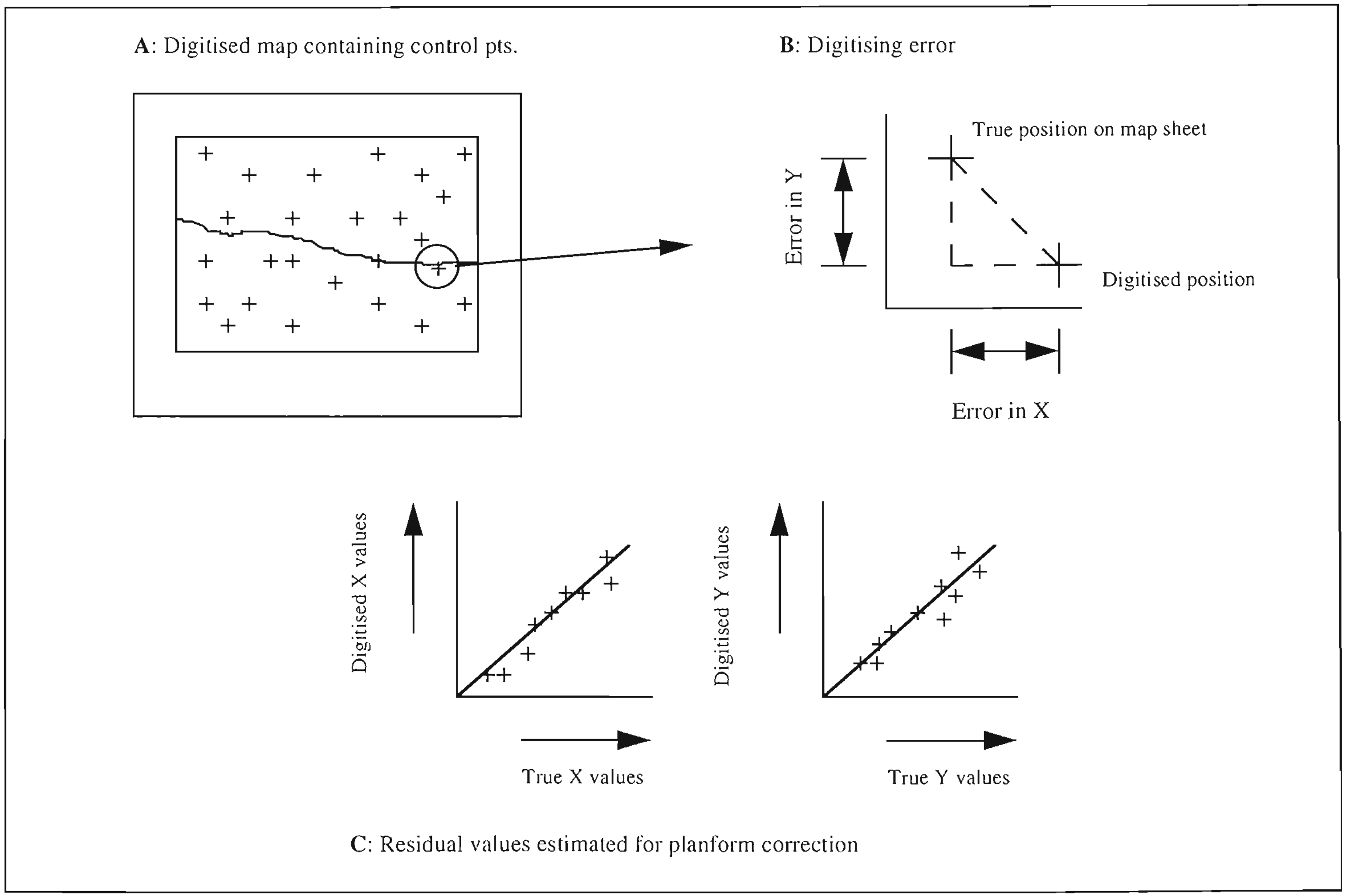


Figure 4.10 Estimation of residual values

c) Unlike cartographic sources of historical information, aerial photography suffers scale distortion across the image the further one moves off-nadir. Such distortion may be accounted for by the assignment of control point values to rectify the imagery. However, Milton and Gilvear (1995) note that aerial images will also suffer as a consequence of relief distortion as a function of the height of an object above the ground. In the case of the investigation of the River Towy the assumption is made that, because river channel features on the floodplain do not display considerable relief variability across the frame, such distortions are ignored.

With these assumptions, residual error values may be estimated for the historical source information.

Example 1

Residual error values are obtained from a photocopy of a 1979 Ordnance Survey Sheet at 1:10000 scale. A total of 39 residual values are obtained. The frequency distribution of these values is normally distributed, such that, they may be used to estimate the exceedence probability for specific deviations. At 95% confidence an error of 2.33m is estimated. The 39 residual point values represent the residual error values obtained from several sheets which make up the coverage for Site B. The assumption is made that because these sheets are all obtained from the same survey and are copied from original in the same manner (photocopied using the same photocopier) that the estimate of residual errors would be minimal between individual sheets. There were insufficient control point values on any one individual sheet to produce a frequency distribution with similar levels of confidence.

As a consequence, any location on the ground represented in the 1979 Ordnance Survey 1:10000 sheet is assumed to be spatially accurate to within 2.33m (at 95% confidence). This value is a surrogate, it cannot account for the surveyor's perceptual error in estimating the location of banktop, the 'normal winter level'.

Example 2

Residual error values are obtained from a photocopy of a 1876 Ordnance Survey Sheet at 1:10560 scale. A total of 38 residual values are obtained. The frequency distribution of these values is normally distributed, such that at 95% confidence an error of 6.77m is estimated.

Temporal inherent error is not deemed problematic to the analysis of river channel planform change for the River Towy using aerial photographs. Without exception, all aerial photographs used in the analysis were individually dated to the nearest hour at the time of the aerial sortie and this information presented with each individual frame. The same was not true for maps used in the analysis. Survey and revision dates are provided to the nearest year. Yearly mean values suffer increasingly from the period between maps.

4.4.3 Operational errors

This section considers the assessment of errors introduced as a consequence of the operational procedure of converting information to a digital formal, conversion between digital formats, and of the analysis procedures themselves. Because the investigator has direct control over these operational procedures he/she has greater understanding regarding the estimation of component errors.

Digitising Error

Digitising error affects the planimetric accuracy of the analysis through introducing transcription errors in the digital representation of the river channel boundary location and the control point values. A series of tests were conducted using information from the River Towy to assess the magnitude of digitising accuracy using SPANS GIS.

Figure 4.11 illustrates that if the same line is re-digitised several times it is possible to assess the distribution of digitising errors. Assuming that these errors are normally distributed it is possible to estimate confidence limits expressed in absolute terms of measurement (in this case millimetres). These limits can then be considered in terms of the scale of the map being digitised.

The experiment was conducted for reaches that are selected from Site B, a site which contains both straight and sinuous channel banks. The experiment procedure was as follows:

a) Reaches were defined along one bank or the river channel at approximately 500m intervals and their start and finish points defined by node points.

b) The river channel boundary is digitised between these two node points and saved as a file. The same line is repeat digitised between the same two node

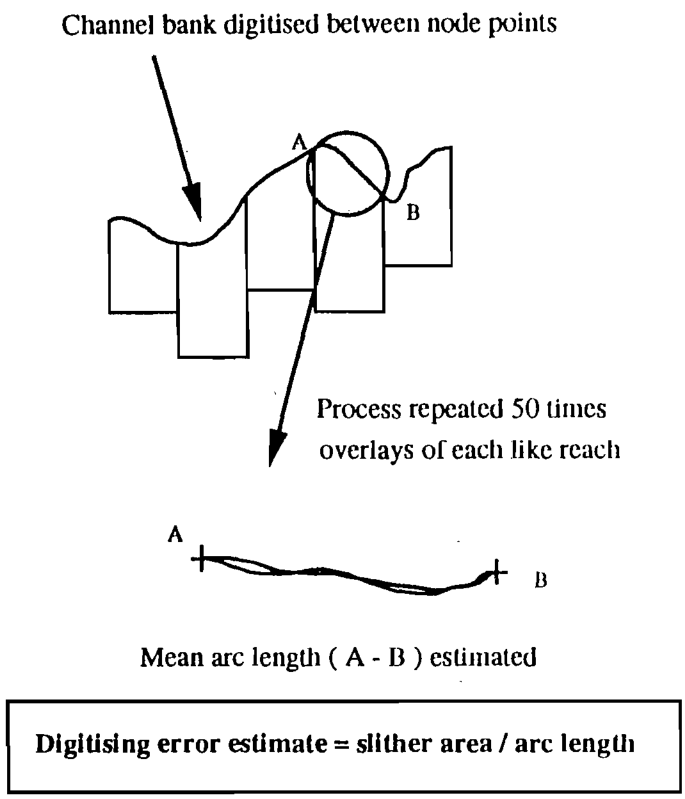


Figure 4.11 Estimation of digitising errors from repeat digitising of the river channel boundary location

values. Using the 'snap to node' digitising function the start and finish points of the two lines are identical. Both are saved as separate files.

c) Each individual file is overlain within the GIS. If the same channel line had been digitised at exactly the same locations then the line displacement between any two files would be perfect with no net gain or loss in channel area.

d) The two (very slightly) different line lengths between the nodes were queried to obtain the mean line length. The aerial change was then divided by the average line length to estimate the average positional error (in mm) of the line.

e) The above process was repeated 50 times using different representations of river channel boundary selected from Site B and a frequency distribution of the positional errors produced. The frequency distribution was found to be normally distributed. This allows the calculation of the 95% confidence limit at which the river channel planform changes observed from the overlay of the historical sources are 'true' and unlikely to be the product of digitiser error.

Two standard deviations from the mean (enclosing 95 % of the area under the curve) were chosen as an estimate of the probable threshold between distinguishing error and the positional change. This threshold was estimated as 0.20245mm - indicating a margin of 2.0245m for maps of 1:10000 scale.

Information Format Conversion

In digital form information is converted from a vector format to a raster format to allow for the analysis of Area Map Overlays. The conversion process requires that the investigator specifies the resolution of the raster grid cell. It is important that the level of generalisation imposed by the vector to raster conversion does not exceed the inherent error and operational error introduced up to that point. As historical information is to be compared the chosen grid cell size should be representative of the minimum anticipated error of all the historical sources used in the analysis. In the case of the River Towy this is provided by the 1992 sheet for which inherent errors are assumed to be zero (as this map forms the reference map) and digitising error no greater than 2m at 95% confidence). Cell sizes of 0.5m were therefore deemed suitable to ensure minimal loss of information. This size was selected and fixed throughout the analysis. The trade-off of increasing the cell size is one of information redundancy for all other information sources which results in a increase in computational processing time. Errors associated with information format conversion are, therefore, considered negligible in this case.

4.4.4 Assessment of the propagation of error

The overall error in planimetric accuracy is a function of all of the component inherent and digitising errors propagated by the GIS-based methodology. In many cases it is impossible to assess the magnitude of individual components due to the indeterminate nature surrounding their generation (e.g. perceptual errors). A surrogate value using spatial association provides an estimate for inherent error. Digitising error may be estimated from the test as indicated. In both cases these errors may be expressed to varying levels of confidence. As such, these values may be substituted to estimate a value of Total Error. The relationship between these component errors remains indeterminate because the digitising process is used itself as a basis for estimating control point locations. Therefore, the analysis of the propagation of spatial errors throughout the river channel planform analysis must assume a 'worse case scenario'. This assumes a case where any given point location is laterally displaced in the same direction by the component inherent and operational errors:

Total Error may therefore be estimated as a Total Probable Maximum Error (TPME). This is illustrated in Figure 4.12. TPME may be considered as the sum of component inherent and operational errors:

TPME = (Component inherent errors) + (Component operational errors)

By substitution of surrogate indices

TPME = (Residual Error) + (Digitiser Error)

TPME may therefore be estimated for different historical sources of planform information at different scales of representation and with different levels of confidence (Figure 4.13).

For example, substituting the 95% exceedance probability values obtained in the examples from 1:10000 scale 1979 and 1:10560 scale 1876 maps the TPME may be estimated at 4.35m and 8.89m respectively. Therefore, this information obtained

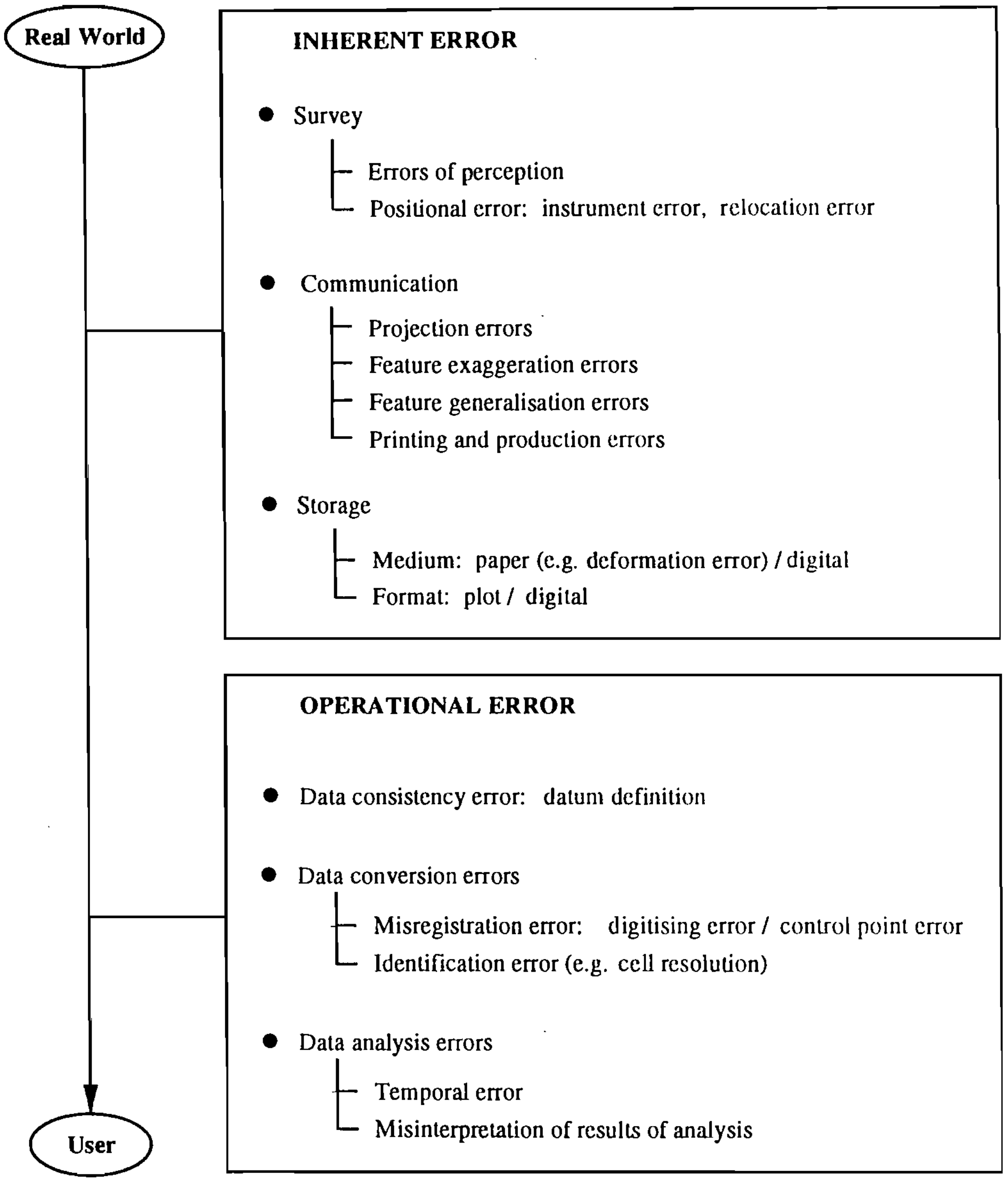
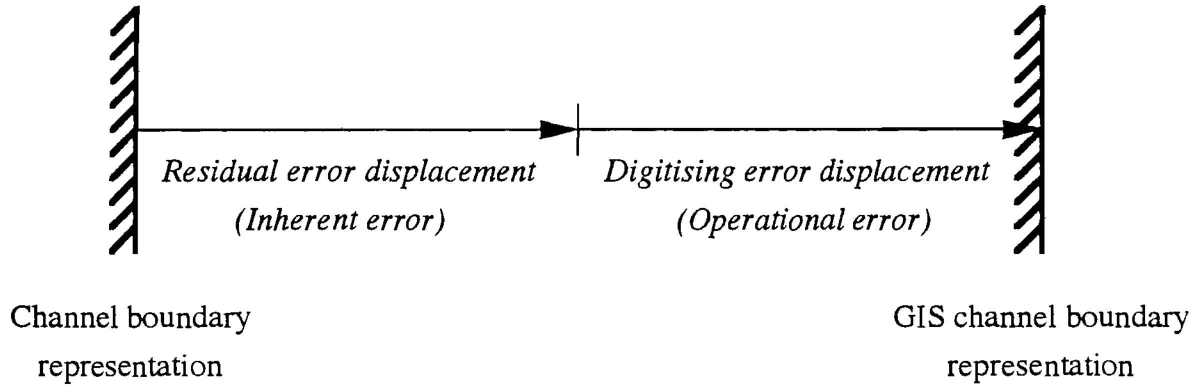


Fig 4.12 The transcription of errors in the comparison of planform information

Estimate of TPME (Simultaneous occurence of both errors)



Level of confidence	Error estimate, mm (At 1:10000 scale,m)			Probability of exceeding TPME
	Residual error	Digitising error	TPME estimate	
90% (0.900)	0.652 (6.52)	0.194 (1.94)	0.846 (8.46)	1%
95% (0.950)	0.704 (7.04)	0.205 (2.05)	0.909 (9.09)	0.25%
98% (0.980)	0.763 (7.63)	0.218 (2.18)	0.981 (9.81)	0.04%
99% (0.990)	0.803 (8.03)	0.226 (2.26)	1.167 (11.17)	0.01%

Figure 4.13 Estimate of Total Probable Maximum Error

from the River Towy may be used to set limits of acceptable tolerance. A value of 10m at 1:10000 scale may be considered an average approximation of Total Error at a 98% level of confidence.

4.5 CONCLUSIONS

This chapter described how a GIS-based approach can be used to interpolate indices of river channel planform change. The geomorphological challenge investigated in this chapter is to distinguish planform changes with confidence from the inherent errors of the historical source information and the operational errors arising from the methodology.

Of the different methods described no one method is isolated in terms of the most applicable to interpolating overall patterns of river channel planform change. Instead, the methods may be used to their best advantage if they are used in conjunction with each other. Furthermore, dependant on the nature of the geomorphological enquiry, the results may be set against contemporary field-based investigations (e.g. geomorphological reconnaissance surveys) to provide a fuller perspective. In theory it is possible to reproduce the results obtained by the GIS-based approach manually. The decision is based on the nature of the channel change questions asked of the enquiry and the available resources. By comparison to manual methods the GIS approach allows the user to operate at the optimum spatial resolution dictated by the confidence limits such that the historical documented information is fully exploited.

In this chapter the methodology has been demonstrated for reaches of the River Towy. The River Towy was deemed suitable because the geomorphological problem (disseminating planform adjustment) associates with information type (planform information) fulfilling the requirements outlined in Section 4.2.1. The methodology developed for the River Towy has been demonstrated to be effective because it is able to discriminate river channel planform changes with confidence over the period of the historical record.

Information assessed for the River Towy would suggest that, were the same methods employed at the same scale of river channel representation (approximately 1:10000), then channels much less than 10m in width would be approaching the minimal level of tolerance with which planform changes may be discriminated from potential inherent and operational errors. Therefore, in the absence of corroborating information, at a planform scale of 1:10000:

a) River channels less than 10m bankfull width are likely to yield unreliable quantitative estimates of river channel planform change.

b) Quantitative estimates of river channel planform change may be deemed reliable where the magnitude of lateral movement between any two chosen representations of a channel bank width exceeds 10m.

c) Where either/or channel bankfull width is less than 10m and/or lateral displacement is less than 10m, this is not to assume non-adjustment but rather that the confidence with which these changes may be regarded as 'true' representations of change is diminished.

The relative accuracy of the analysis of river channel planform change may only be improved by increasing the spatial resolution of the inherent source information and/or by improving the efficiency of data transcription (e.g. digitising accuracy). On the basis of the methods presented for the River Towy it is possible to identify confidence limits for historical planform information of varying spatial resolution, but it must be remembered that these values are attributed closely to the GIS-based software used in their dissemination. The values so presented therefore provide an indication of patterns of planform change and associated error limitations but are not presented as gospel.

These results have important implications for river channel management. They allow the investigator to attach confidence to the results of river channel planform change enquiries. Through the systematic evaluation of the geomorphological problem in association with historical information type the method provides a safeguard against drawing inappropriate conclusions (and potential river channel management decisions) from the planform information. This my lead the investigator to seek alternative sources of planform information (e.g. at a greater spatial resolution) or to seek alternative methods for extrapolating river channel change information.

4.6 SUMMARY

A GIS methodology has been demonstrated as a means of representing river channel planform change for selected sites for the River Towy from a sequence of historical planform records (maps and aerial photographs). River channel planform change may be quantified in terms of lateral displacement of the representation of river channel bankfull, area displacement of a selected reach and, where sequences of historical information are available, to observe changes in channel occupancy as a surrogate for river channel planform stability.

The GIS methodology allows the investigator to place confidence limits on the results of the investigation. This allows the investigator to determine 'true' planform changes from those of errors inherent in the historical sources and the operational errors introduced by the nature of the GIS methodology by examining the transcription of these errors. Error analysis has demonstrated that, for historical planform information representing river channel boundary locations at a scale of approximately 1:10000, a river with a bankfull width of less than 10m will produce unreliable indices of planform change. Additionally, when considering any two representations in time from the historical record, a planform change of less than 10m cannot be deemed to be a 'true' change, but may represent the sum of the transcribed inherent and operational errors.

These results have been shown to have implications for the assessment of planform change for other river channels. They direct the investigator to pay close attention to the spatial scale of the river channel under investigation with respect to the nature of the historical planform sources available for the interpolation of planform change. Where planform changes cannot be demonstrated to be 'true' he/she must accept a lesser degree of confidence in the results of the investigation or seek alternative sources of information and/or alternative methodologies with which to represent river channel planform change. These results would suggest that these methodologies are best suited to relatively dynamic river channels and are largely unsuited to lowland river channels in England and Wales.

CHAPTER 5

THE EXTRAPOLATION OF HISTORICAL RIVER CHANNEL CHANGE FROM CROSS-SECTIONAL INFORMATION: THE RIVER SENCE, LEICESTERSHIRE.

5.1 INTRODUCTION

Historical maps and aerial photographic records at a variety of scales provide invaluable sources of information about changes in river-channel planform location. Chapter 4 describes a GIS-based approach for analysing these historical information sources by the overlay of the digital representations of river channel boundary locations at specific dates selected from the historical record. Chapter 4 uses planform information obtained for the River Towy, Dyfed to demonstrate how the approach is successful in discriminating stable and unstable reaches for three chosen study sites.

Furthermore, the GIS-based methodology provides a unique basis for estimating the accuracy with which planform changes may be confidently quantified set against the 'noise' of components of inherent and operational errors. Chapter 4 makes two general observations:

a) As the Scale of representation of the channel width decreases so the ability accurately to represent the location of this boundary decreases.

b) As the magnitude of the planform adjustments decrease between any two given dates from the historical record, so the ability confidently to predict change decreases. Absolute error values have been estimated for given scales of representation and levels of confidence using data obtained for the River Towy and are represented in Table 4.13.

By increasing the spatial resolution of the historical information the investigator may be able to overcome some of these challenges, however, there will remain limits to which planform information will be able to extrapolate answers to river channel change questions. Confidence in the results is demonstrated because the physical size of the river-channel and the representation of channel width at a scale of 1:10000 is sufficiently large digitally to represent the channel boundary locations accurately, and, the river's planform change between chosen dates which typically lie beyond the error boundaries suggested by the Total Probable Maximum Error. The River Towy is perhaps typical of many upland and piedmont zone rivers in England and Wales such that it is perhaps fair to assume that the methodology may also be successfully applied to any number of similar rivers given the supporting historical information.

Chapter 2 reviews of previous studies in England and Wales where historical planform records have been used to reconstruct planform change. Observing where these studies have been located shows the majority of them to be situated in the upland and piedmont zone areas, (e.g. Hooke and Redmond, 1989). This is unsurprising considering that the size and magnitude of river channel planform adjustments are well suited to such analysis. However, it should not be concluded that the lesser energy rivers of lowland Britain are necessarily inactive on the basis that they may exhibit smaller absolute planform adjustments, but rather, methodologies employing map and aerial photographic evidence to detect river channel change are limited in their confidence to detect channel change by virtue of their limiting spatial resolution. The application of the GIS-based methodologies (e.g. described in Chapter 4) to such rivers, whilst enhancing the opportunities for detecting changes over manual comparisons, is likely to conclude that, on the basis of planform evidence alone, these rivers may be assumed to be stable were a similar index of channel adjustment to be employed. Certainly this would be a fair conclusion were we to adopt the same method of classification for all rivers in England and Wales (this is reflected in the review in Chapters 2). However, geomorphological field investigations and management experience have consistently shown that there are clearly significant changes occurring on such lesser energy rivers. While the planform record is likely to be able to discriminate gross changes in channel position (e.g. cut-off and realignment) the ability to detect the more subtle changes in channel form is handicapped at scales of spatial resolution similar to those employed for the River Towy investigation. Typically, in assessing the stability of the lowland river channel the river channel manager must rely upon intuition and information obtained from contemporary baseline surveys (e.g. geomorphological reconnaissance) in order to reconstruct changes in channel form from which to infer channel forming processes.

Contemporary geomorphological survey evidence, adopting catchment-based approaches provides an effective means to determine strategies for river channel management. However, as with more active rivers of England and Wales, the opportunity to place contemporary observations within a historical framework would further enhance the ability with which to base management decisions.

Given the restrictions presented by the limiting resolutions of planform evidence, alternative sources of historical information must be employed to detect change. This chapter aims to examine the ability of historical cross-sectional information to extrapolate historical river channel change and considers the implications of this information to aid geomorphologically sensitive river channel management. This chapter investigates data obtained from historical cross-sectional information for a regraded river-channel, the River Sence in Leicestershire. The chapter describes the use of a GIS-based approach to integrate information extrapolated from temporal sequences of cross-sectional records with the spatial distribution of this information and to employ this information to describe changes in space. The chapter assesses the errors involved in the proposed methodology as a basis for determining the limitations and application of historical cross-sectional investigations on other river channels. In combination with contemporary field evidence the historical information is then used to describe river channel change on the River Sence for the period of historical observation. The specific objectives of this chapter are as follows:

a) To provide a rationale for the choice of the study site.

b) The presentation of a methodology for assessing river channel change based on the available cross-sectional information for the River Sence.

c) Assess the errors associated with these methodologies.

d) Assess the significance of the results in terms of their ability to promote an understanding of historical river channel change and their ability to aid geomorphologically sensitive river channel management.

e) Consideration of river channel change 1966-1993 for the study reach of the River Sence.

5.2 THE STUDY SITE: THE RIVER SENCE, LEICESTERSHIRE.

5.2.1 Rationale for the choice of study site.

The River Sence, Leicestershire is chosen in this study on the following basis:

a) The physical dimensions of the river channel and its planform activity are small in comparison with many upland and piedmont zone rivers.

b) For the chosen study reach (see Section 5.2.2) there are complete sets of cross-sectional records detailing surveys made at the same cross-section locations on three occasions from 1966. These surveys provide the information required for a thorough investigation of the utility of historical cross-section records in investigating river-channel change.

c) The River Sence has been subject to considerable channel management, including the River Sence Improvement Scheme, which was responsible for the regrading of the channel through the study reach from 1973 and subsequent routine maintenance (from 1989) which has attempted to alleviate within-channel deposition of sediment. The River Sence has demonstrated a widespread morphological response to the regrade which has been documented within the literature and which represents a clear example of an engineering-based approach which has proved to be inappropriate to the successful management of a river channel.

5.2.2 A background to the River Sence and the study reach

The River Sence is located to the south-east of Leicester, flowing Westwards to its confluence with the River Soar (Figure 5.1). It has a mean annual discharge (1971-1975) of $2.4m^3.s^{-1}$ (Sear, 1993). Its catchment area is $135.8km^2$ (estimated digitally from contours from 1:25000 scale Ordnance Survey sheets). The River Sence is underlain by the Lower Lias beds, which consist of brown micaceous silty clay, and approximately 1m depth of dark loamy alluvium containing scattered Bunter pebbles and flints derived from local glacial drifts. The low permeability of the catchment's clayey soils results in high runoff rates, producing a flashy flow regime. The cohesive nature of the sediments can support steep bank angles before failure, with the result that planform adjustments are minimal. The River Sence floodplain supports pasture and arable land use, which either extends to the edge of the channel or, where the banks are fenced, is separated by a narrow strip of riparian vegetation. Urban land use is restricted mainly to the north-west of the catchment at Wigston, although small rural settlements are scattered throughout the catchment.

The channel reach investigated in this chapter is 2.4km long and flows between Kilby Bridge at the upstream limit (SP 609970) and Crow Mill (SP 590976) (Figure 5.1). This reach is selected on the basis of the available cross-sectional information.

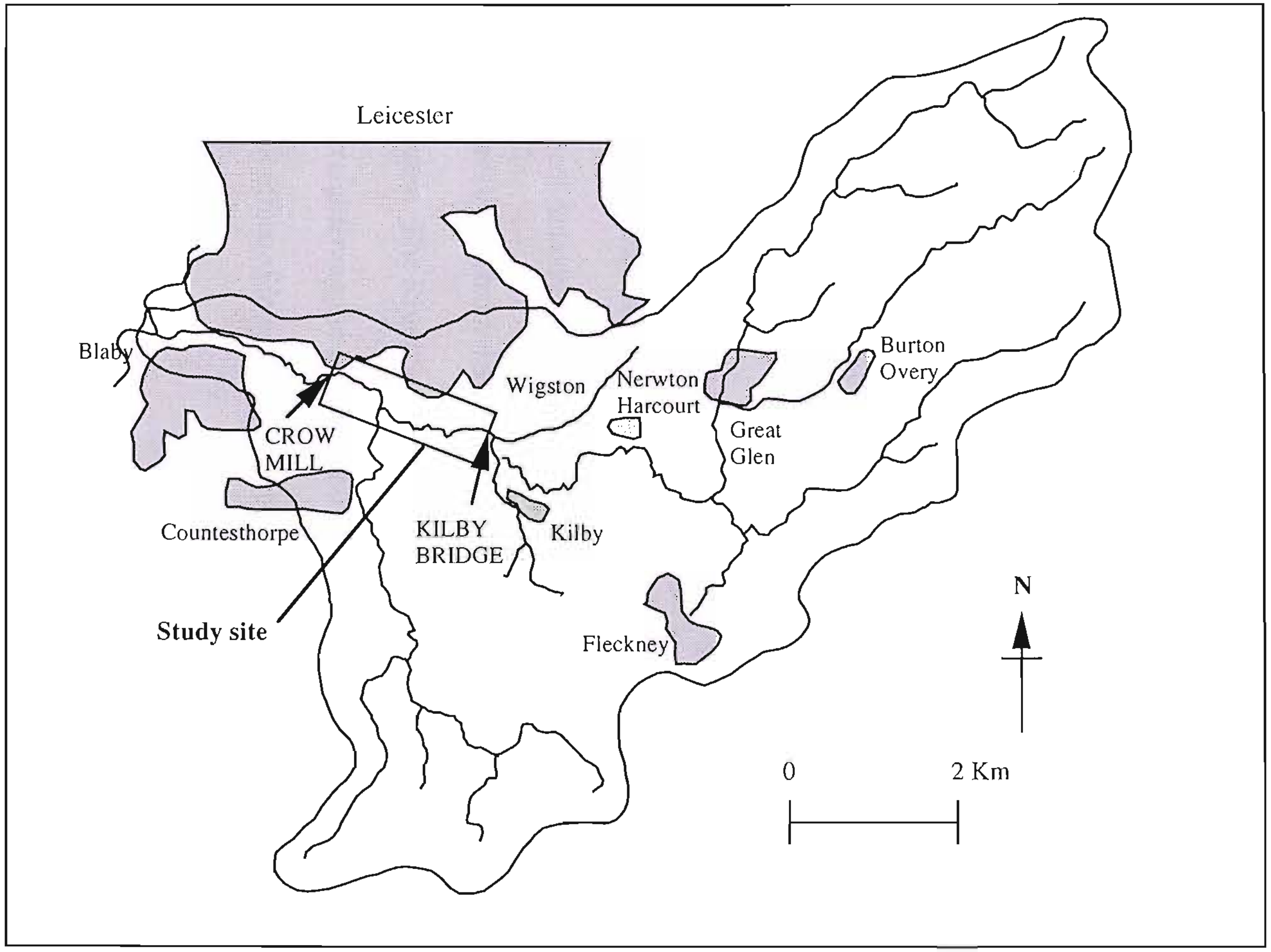


Figure 5.1 River Sence catchment and study site location

While it is accepted that in applied studies it is usually inappropriate to demit the area of study on the basis of the available information it was deemed reasonable in this instance because the chapter is demonstrating a methodology. Furthermore, the reach is extensive and continuous, contains both straight and meandering sections and, was regraded in 1973 as part of the River Sence Improvement Scheme.

5.2.3 Recent history of the study reach.

The following analysis of morphological information for the study reach of the River Sence considers the period 1966 to present. This is the period for which cross-sectional records are available, and it includes the River Sence Improvement Scheme (1973) and the 1989 major maintenance of the channel. Prior to the Improvement Scheme the Sence catchment had a history of flooding which had been exacerbated by the implementation of widespread arterial drainage and urban runoff. The River Sence Improvement Scheme was designed to alleviate flooding by increasing the capacity and slope of the channel and thus its ability to contain and efficiently transmit flood-water. The River Sence Improvement Scheme involved widening, deepening and straightening the channel. Lowering of the channel bed would have had the additional effect of lowering the water table of the land immediately adjacent to the channel.

The study reach underwent a major regrade from 1973, which involved cutting a trapezoidal channel-section. This was undertaken by working in an upstream direction from the River Soar confluence. Natural stability of the channel has been disrupted as a result of the regrade because of the dramatic change in the physical characteristics of the channel combined with alterations to channel flows and sediment transport. Sear and Newson (1993) note that in the post-regrade history of the River Sence there have been two main potentially de-stabilising discharge events, the highest recorded flood in 1975, half way through the implementation of regrade, followed the next year by the 1976 drought with the lowest recorded discharge for the river. Over-widening of the channel and over-steepening of its banks has led to bank failure and within-channel sedimentation. These sediments are readily colonised by vegetation, which in summer may partially throttle channel flows and locally impede flows. As a result, the reach has undergone periodic routine maintenance to dredge the low-flow channel and remove excessive weed growth. Sear (1993) notes several consequences of the regrade and proposes a model for the re-adjustment of the channel (Figure 5.2):

a) Over-steepening of the channel banks results in excessive bank failure through slumping and multi-component bank profile.

b) Within the resultant two, or multi-stage channel, vegetation colonisation of the lower bank sections acts as a sediment trap. Vegetation further colonises the deposited sediment and serves to stabilise the banks providing added bank toe protection and to restrict scour.

c) Widespread sedimentation reduces the channel capacity below the design capacity of the regrade, necessitating periodic maintenance in order to dredge the channel of fine sediments. This re-initiates instability within the channel.

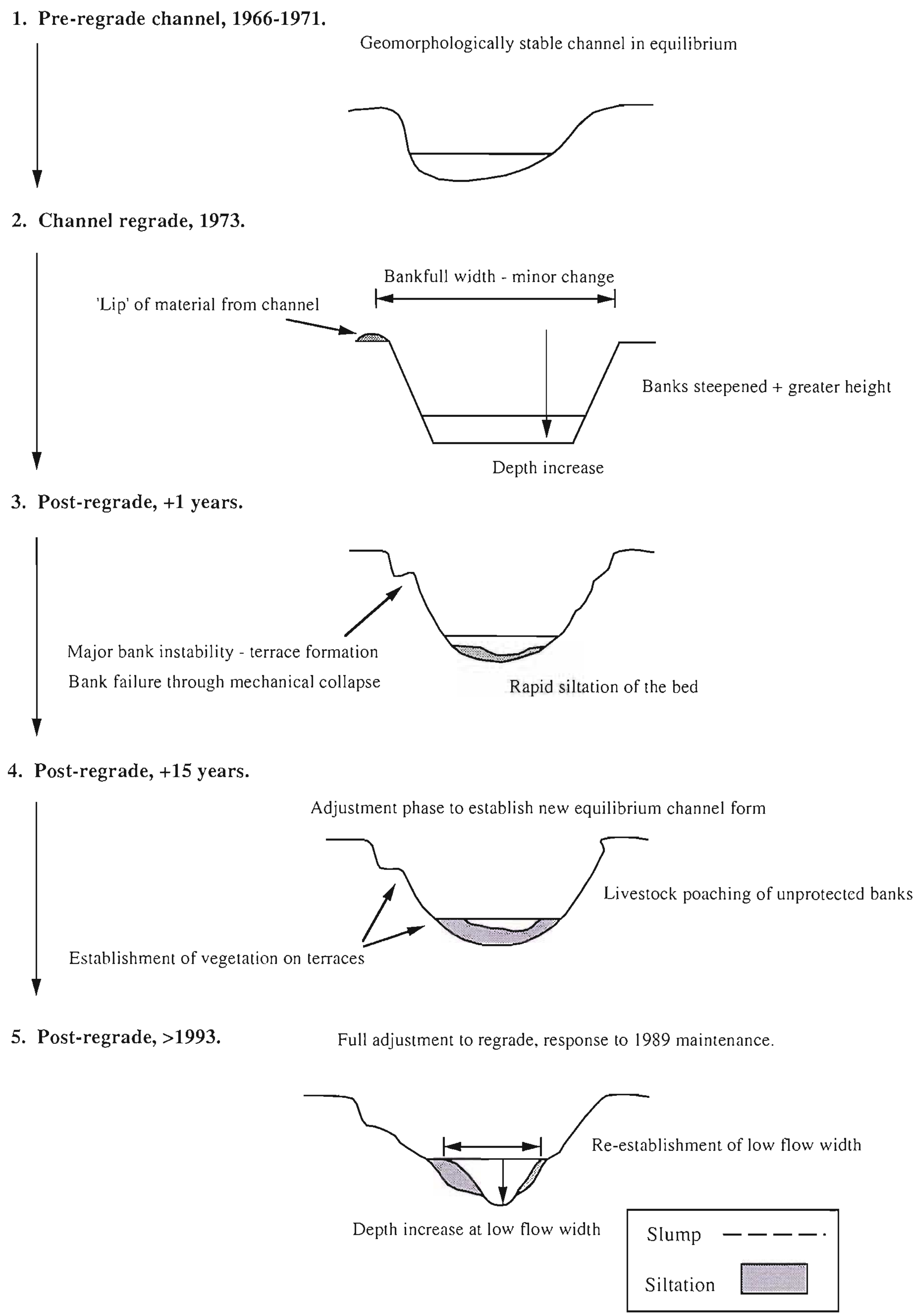


Figure 5.2 Five Stage model of channel change on the River Sence (adapted from Sear, 1993)

5.3 A METHOD FOR IDENTIFYING AND QUANTIFYING RIVER CHANNEL CHANGE FROM CROSS-SECTIONAL INFORMATION

5.3.1 Methods in the study of river channel change from cross-sectional information

Cross-sectional information allows the investigator to extrapolate river channel change information through comparisons of cross-sectional records obtained at different moments in time. The assumption is made that the cross-sectional record is either:

a) Relocated in space allowing comparisons of individual cross-section locations through the direct comparison of cross-sectional form.

b) Cross-sections are not relocated precisely in space (there may be a differing number of cross-sections in each survey), but may provide sufficient information on which to estimate semi-quantitative changes between reaches in space and time.

This investigation considers the former, although with reservations indicated in Section 5.4 concerning the assumption regarding the 'precision' of the re-location. The second case is considered in greater detail for the comparison of ground-based oblique photographs in Chapter 6.

The nature of the comparison is dependent on the characteristics of the cross-sectional information. Where information is provided in topographic survey form this may allow varying means of direct comparison:

a) 'Overlay' procedures (akin to the overlay of graphical representation of planform information) whereby the graphical representation of the cross-section may be overlaid manually or digitally at identical scales of representation. The axis representing the vertical dimension may be exaggerated equally in both cases to highlight within-channel features.

b) Extracting quantitative indices of cross-sectional form from the individual cross-sections. These values may be compared statistically and/or mapped spatially to exhibit cross-sectional change between sections.

5.3.2 Historical cross-sectional information for the River Sence

Cross-sectional information is available for the River Sence in 1966 and 1971. Both of these sequences of record pre-date the River Sence Improvement Scheme of 1973. The 1971 cross-sectional representations also provide an overlaid representation of the 'design' section for the regrade channel. The assumption is made that the 1973 channel is excavated to these dimensions and, as such, the representation provides a record of the cross-sectional channel form immediately following excavation in 1973.

A total of 37 cross-sections were surveyed for the study site of the River Sence. The 1971 cross-sectional survey attempted to replicate the locations of the 1966 cross-sections. Individual cross-section locations are represented in planform on sheets at 1:2500 scale accompanying the 1971 re-survey.

Individual cross-sections are presented graphically, depicting the cross-sectional form of the river channel. Additionally, individual horizontal and vertical ('x' and 'y') point information for every survey measurement is provided for each cross-section (Figure 5.3). This is particularly helpful to the investigation for three principle reasons:

a) Reducing information transcription error because indices of cross-sectional form may be extracted directly and are not subject to graphical representation errors.

b) Cross-sections may be re-plotted digitally at desired scales of representation allowing overlay comparison.

c) It provides a basis for estimating the spatial resolution of the cross-sectional survey with respect to the survey accuracy of individual points and in the representation of river channel features through association between values.

In the latter case, each cross-section is represented by approximately 10-20 survey point values. Survey points extend beyond the perceived banktop limit to the floodplain. The cross-sections were observed to have been recorded by surveying breaks of slope.

The 1966 and 1971 survey information is augmented by conducting a contemporary survey of river channel form. This was undertaken in 1993. The 1993 survey sought to relocate cross-sections on the basis of the supporting planform information. The level of spatial resolution of the 1993 re-survey intentionally attempted to

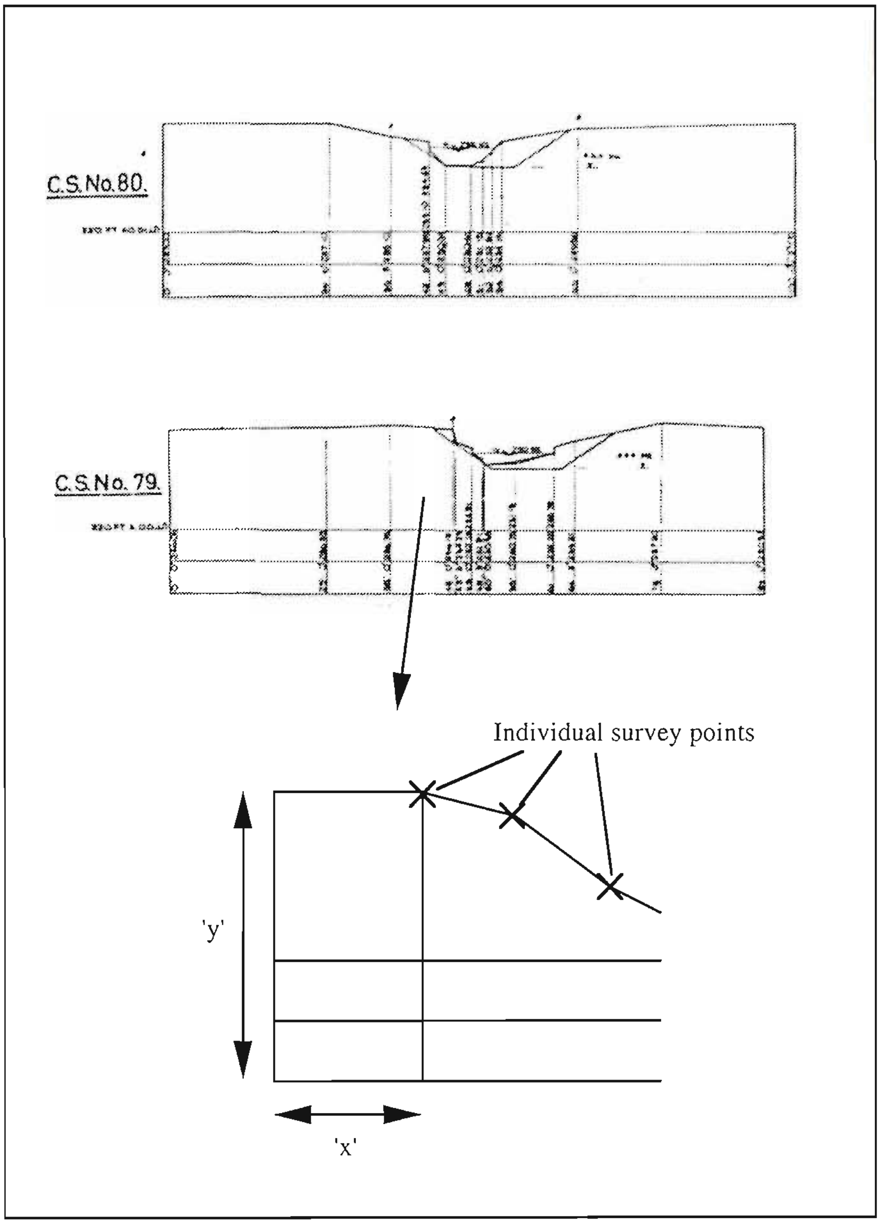


Figure 5.3 Example cross-section information (1971/3) for the River Sence

Individual 'x' and 'y' values for each survey point are provided approximate that of the earlier surveys, e.g. the number of survey point values to represent the cross-section and locating breaks of slope.

5.3.3 Information collection

Unlike planform information considered in Chapter 4, all the cross-sectional information is collected in original format. Furthermore, values for each individual survey point are provided for each cross-section. In this instance therefore, information collection simply involved the transcription of x and y survey point values directly to a computer spreadsheet. Values obtained in the 1993 re-survey are noted manually in the field and values added to spreadsheets in exactly the same format and manner. Spreadsheets are, therefore, produced for each of the 37 cross-section locations representing the cross-sectional form of the study reach for 1966, 1971, 1973 and 1993.

5.3.4 Information handling

Cross-section information was compared by comparing both the graphical representation of the cross-sectional form and through the comparison of channel form indices for each cross-section. In order to allow such comparison it was necessary to define a common datum level to provide standardisation between sections and at different dates from the historical record (Petts, 1977, 1978). The datum level used in this study has been defined at the channel bankfull level. However, both the literature and practice have demonstrated the precise definition of the bankfull channel is not clear-cut and this junction may be estimated by several different means. Petts (1978) observes, "Observation of a simple, uniform channel cross-sectional form, having a plane bed bounded by two single element banks intersecting the floodplain at a sharp angle, is uncommon in natural channels." (p.86)

Unlike the overlay of planform information where individual images may be registered and rectified there may be an absence of 'control points' or locations in the cross-section which can be assumed to be stationary between survey dates. It is possible that repeat cross-sectional surveys may be defined with sufficient resolution from the accompanying planform information as to locate the positions of start and end point locations with relation to a fixed planimetric datum (e.g. Ordnance Survey National Grid Co-ordinates). Alternatively, cross-sections may be relocated with respect to pegs marking the position of the section in the field; if the peg locations are represented in the cross-sectional survey (and are assumed not to have moved between surveys) then cross-sectional representations may be reliably registered. In the absence of control values the investigator may have to make a conscious decision regarding the alignment of the cross-sections. This may be easier to achieve in the vertical axis by assuming a constant floodplain level. The assumption is made that there has been minimal vertical accretion between surveys. In the horizontal axis, provided simply with topographic information, the investigator has no obvious means with which to align the sections. Reaches that are straight might be considered to display comparable levels of change for both banks (assuming the controlling conditions of both banks near-identical) such that the mid-point of the channel (as defined by the mid-distance between the banktop locations) may be selected as a basis for horizontal alignment. However, such assumptions may lead to a mis-representative estimate concerning the nature and direction of lateral adjustment. Corroborating morphometric evidence may prove helpful in this respect and may potentially be supported by field evidence.

Definitions for determining channel bankfull are considered. Bankfull estimates may be made on the basis of discharge (a regime approach) or morphometry (a hydraulic geometric approach). These differing approaches are considered in terms of their usefulness to the analysis of cross-section records.

Bankfull as defined by channel discharge

River-channel cross-section form varies (independently of local controls such as channel roughness and slope) in accordance to a range of discharges, their temporal variation and sediment load. Kilpatrick and Barnes (1964) suggest that a consistent channel level may be defined by considering a consistent channel discharge datum and plotting the level of the water surface through the reach. In this way the discharge that fills the channel to maximum capacity, the bankfull capacity, may be said to define the bankfull discharge. Pickup and Warner (1976) note the tendency for the bankfull discharge to approximate the dominant discharge and Hey (1978) defines the dominant discharge as,

"The constant flow that develops the same gross shapes and dimensions as the natural sequence of discharges." (p.879)

However, values obtained in this manner may be misleading for several reasons:

a) The channel cross-section approximates its form in accordance to the dominant discharge, it is not the product of any one such discharge but a range of flow conditions.

b) The water surface is not itself constant throughout a study reach due to variable bed and bank topography.

Important also is that in the absence of synchronous discharge records the ability accurately to determine the bankfull capacity is subject to increased error. Given additional complications added with dis-homogeneous roughness values and variable sediment loads through the study reach over the historical time scale of enquiry then this serves to illustrate difficulties of using a discharge measurement with cross-sectional records that may represent purely topographic historical information.

Bankfull as defined by the physical geometry of the channel

The datum level used in this study is based upon the physical estimation of the channel bankfull level obtained from the physical geometry of the channel.

Definition of the bankfull level from the cross-sectional geometry may be estimated by different criteria. Wolman (1955) suggested that the channel bankfull level is the elevation at which the width-depth ratio is a minimum. This works well in the case of the 1973 regrade cross-sections given the uniform trapezoidal nature of the cross-sections. However in the case of the pre and post regrade cross-sections the use of the minimum width-depth ratio to define a common datum is flawed in that the difference between minimum width-depth ratio values for any given cross-section is typically small and as such highly sensitive to small changes in the measurement of channel width. As such, it may define any number of stages within the cross-section. Small scale surveying errors in width may give rise to the adoption of a completely different value being taken to represent the minimum width-depth ratio, especially in a channel containing a number of different bench levels such as observed in the 1993 post regrade channel cross-sectional survey. Such errors are not believed to be uncommon as the experiment conducted on the Highland Water in Chapter 3 demonstrates.

The definition adopted in the present study was to estimate channel bankfull on the basis of the level which best corresponds to a change in the relationship between the cross-section and the immediate level of the floodplain surface (Leopold *et al.*, 1964; Woodyer, 1968), Petts (1978) describes this level as a major break of slope separating a well defined channel from a mature floodplain or bench. This level may potentially be the most significant as it represents the level at which water just fills the channel without spillage (Harvey, 1969). Further increases in channel stage would over-top the channel to the floodplain. In practice however this level is not necessarily so clearly defined, the level of floodplain may itself be unclear, particularly where the bank tops are graded to the floodplain surface (e.g., the convex inner bank of a bend) or where the valley floor is itself narrow. Using data derived from the River Sence it was also observed that the floodplain heights recorded on either side of the channel were unlikely to be the same and may vary at a section by up to 0.5m. In the River Sence example the problem has been compounded because the 1993 cross-section re-surveys typically record a 'lip' of material at the banktop level. This 'lip' is believed to comprise material dumped from the channel regrade. In many cases this material is vegetated and stabilised making its immediate identification in the field difficult.

Riley (1972) provided a refined approach with the estimation of a 'Bench Index' (Figure 5.4), The Bench Index considers the relative slope between every surveyed point in the cross-section. In this way horizontal channel segments have a low Bench Index value, whilst vertical sections have a relatively high Bench Index value. The channel bankfull level is defined by the value of the Bench Index with the highest elevation, the first Bench Index minimum. The accuracy of this approach in part depends upon the spatial resolution (spacing) of the survey co-ordinates (the spatial resolution of the cross-sectional survey).

Using a bankfull level defined by the Bench Index, estimates of bankfull width and mean and maximum bankfull depth is then derived for each cross-section at each date in the historical sequence. This information may then be used to compare channel dimensions for the same cross-section location at different dates. However, these channel dimensions are insufficient uniquely to describe the channel cross-section form. Hey (1978) and Richards (1976) observe that for any set of values of channel width and average depth, a variety of cross-sectional forms may be described. For example, cross-sections of the River Sence commonly exhibit complex bank profiles so that the comparison of bankfull cross-section area from any two dates in the historical record could indicate no net change (a balance between erosion and deposition), but the channel may have undergone lateral migration or a marked change in the shape (Figure 5.5). Unlike the GIS-based planform approach where, for a given reach, estimates were provided for both net erosion and net deposition, the methodology suggested here provides only summary

Left bank data

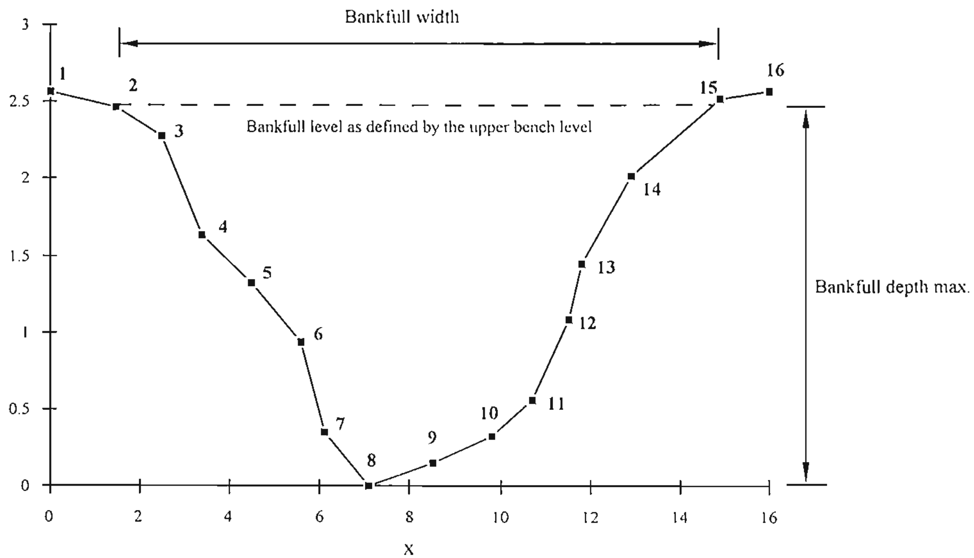
i	*Width (i)*	*Depth (i)*	*BI*
1	14.68	2.56	19.5
2	12.73	2.46	5.95
3	11.6	2.27	4.44
4	8.76	1.63	5.03
5	7.2	1.32	4.03
6	5.67	0.94	3.2
7	3.78	0.35	*
8	*	*	*

Right bank data

i	*Width (i)*	*Depth (i)*	*BI*
16	*	*	*
15	*	*	*
14	10.05	2.02	4
13	7.73	1.44	4
12	6.33	1.09	2.92
11	4.78	0.56	4.96
10	3.64	0.33	10.05
9	1.93	0.15	*
8	*	*	*

Left Bank

Right bank



Bankfull level defined at i=2, from which statistics obtained :

Bankfull cross-section area = 17.09 square metres

Bankfull width = 12.73 metres

Bankfull depth maximum = 2.46 metres

Figure 5.4 Estimation of the channel bankfull level employing Riley's bench index (Riley, 1972)

All bankfull indices are defined to a common datum. This example shows cross-section no. 67

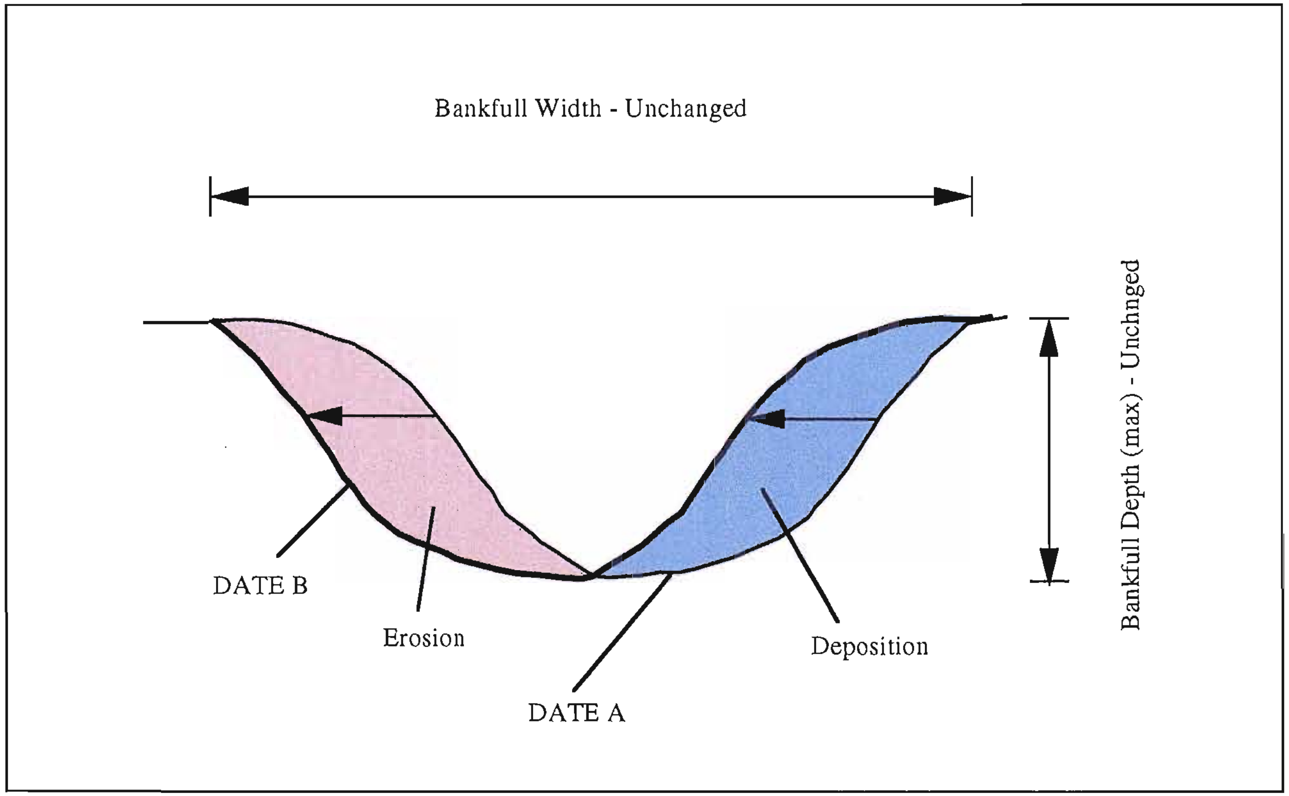


Figure 5.5 Perceptions of cross-sectional change

Two cross-sectional are represented, date A and date B. The channel has migrated laterally. Indices of change (e.g. bankfull width and maximum bankfull depth) may remain unchanged statistics of net balance. However visual qualitative examination in the change in channel form below the bankfull level could provide an indication of morphological change, even if it could not support direct estimates of erosion and deposition for that section.

Furthermore, if it were possible to incorporate a vertical attribute of the location of each cross-section in the horizontal plane it would be possible to construct a digital terrain model of the study reach within the GIS. In theory this would allow volumetric estimates of erosion and deposition to be calculated between dates from the historical record (e.g. Milne and Sear, 1997). While the technical possibilities exist for such an approach it is not feasible in the case of the River Sence data because the precise locations of the cross-sections in the horizontal are not accurately defined and because the down channel resolution of cross-sections is deemed gross realistically to portray the channel form.

5.3.5 Information analysis

Analysis of individual cross-sectional form

The analysis of cross-sectional form is through two means of analysis:

a) By comparing the 'shape' of the cross-sections through graphical comparison.

b) By the analysis of indices of cross-sectional form extracted from each cross-section. In the case of the River Sence this was confined to the estimate of bankfull cross-sectional area, bankfull width and bankfull depth (mean and maximum).

Horizontal and vertical values from the survey information are input to a computer program, written in Visual Basic by Dr. J. Milne (at the University of Southampton), which is designed specifically for the purpose of estimating parameters of channel form from individually surveyed points.

The computer-based program calculates cross-sectional area, width, and mean channel depth by the construction of horizontal levels across the channel for any chosen co-ordinate. In using this program the risk of gross errors is considerably reduced by comparison to manual calculation (e.g., using a planimeter to calculate area), and standardises the systematic errors. Thus quantitative indices relating to channel form are given for each cross-section at each date in the historical record. Channel cross-sectional change statistics are obtained by the comparison of these channel cross-section form statistics at each cross-section location. Using the survey point values directly in the analysis promotes a reduction in the potential operational error. A stage in the data transcription is thus effectively removed. A planform comparison would be a case where individual survey points were available depicting the channel bank location such that this would negate all digitising errors.

The spatial analysis of cross-sectional change statistics: A GIS-based approach.

Estimates of bankfull cross-section area, width and depth were generated for each of the 37 cross-sections considered within the study reach of the River Sence. These data are then captured and stored as attribute data, referenced by their planform location, within a GIS (SPANS MAP), and can support spatial analysis of channel change between survey dates. As each cross-section has a unique spatial location, the centre-point of the cross-section may be represented as a point superimposed upon the digital representation of the channel centreline within a GIS. Using the TYDAC Technologies' product SPANS MAP attribute data may be attached to each point location of each cross-section reference point. Because location and attribute values are interactively linked in the GIS, specific queries may be addressed by selecting specific attribute data from the spreadsheet and displaying these data spatially, or by defining particular areas from the map and highlighting the spreadsheet information which represents this area. Furthermore, the spreadsheet information may be analysed to produce visual representations of complex queries, such as:

- What is the cross-sectional change between 1966 and 1971 at each section? Represent these changes spatially.

- What is the ratio of cross-sectional change per year 1973-1993 expressed as a proportion of the change values per year 1966-1971? Represent these values spatially.

Examples of selected output from SPANS MAP (GIS) are provided in Figures 5.6 and Figure 5.7.

As with the case of the planform GIS-based methodology described in Chapter 4, the GIS-based approach to representing data from the channel cross-sections does not achieve anything that could not be undertaken manually. However, it does provide several distinct advantages, re-iterating those of the planform approach and summarised by providing a heightened understanding of the river channel change.

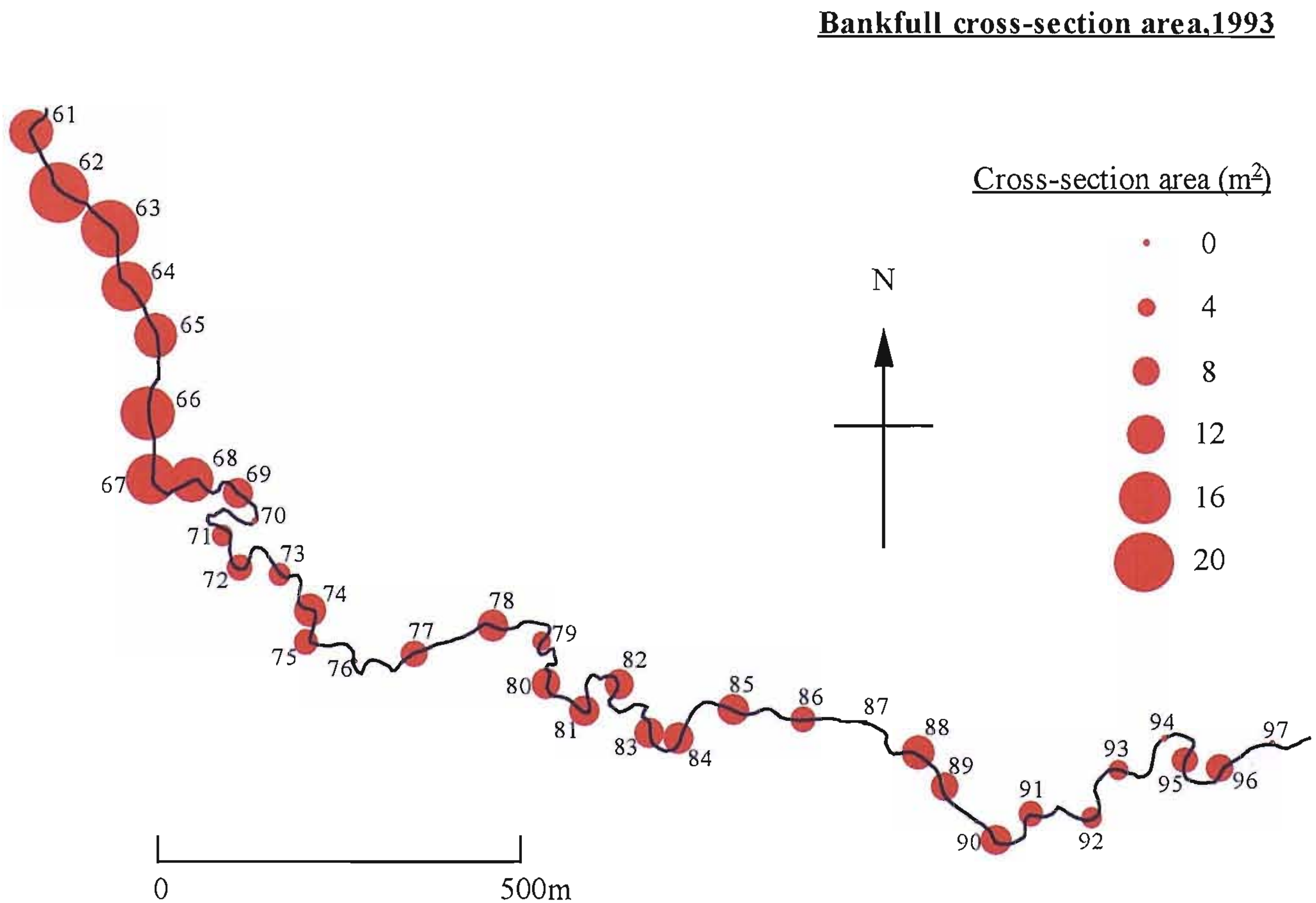


Figure 5.6 Example of SPANS MAP output representing the spatial distribution of attribute values
This figure represents a simple query to show one variable at one date only

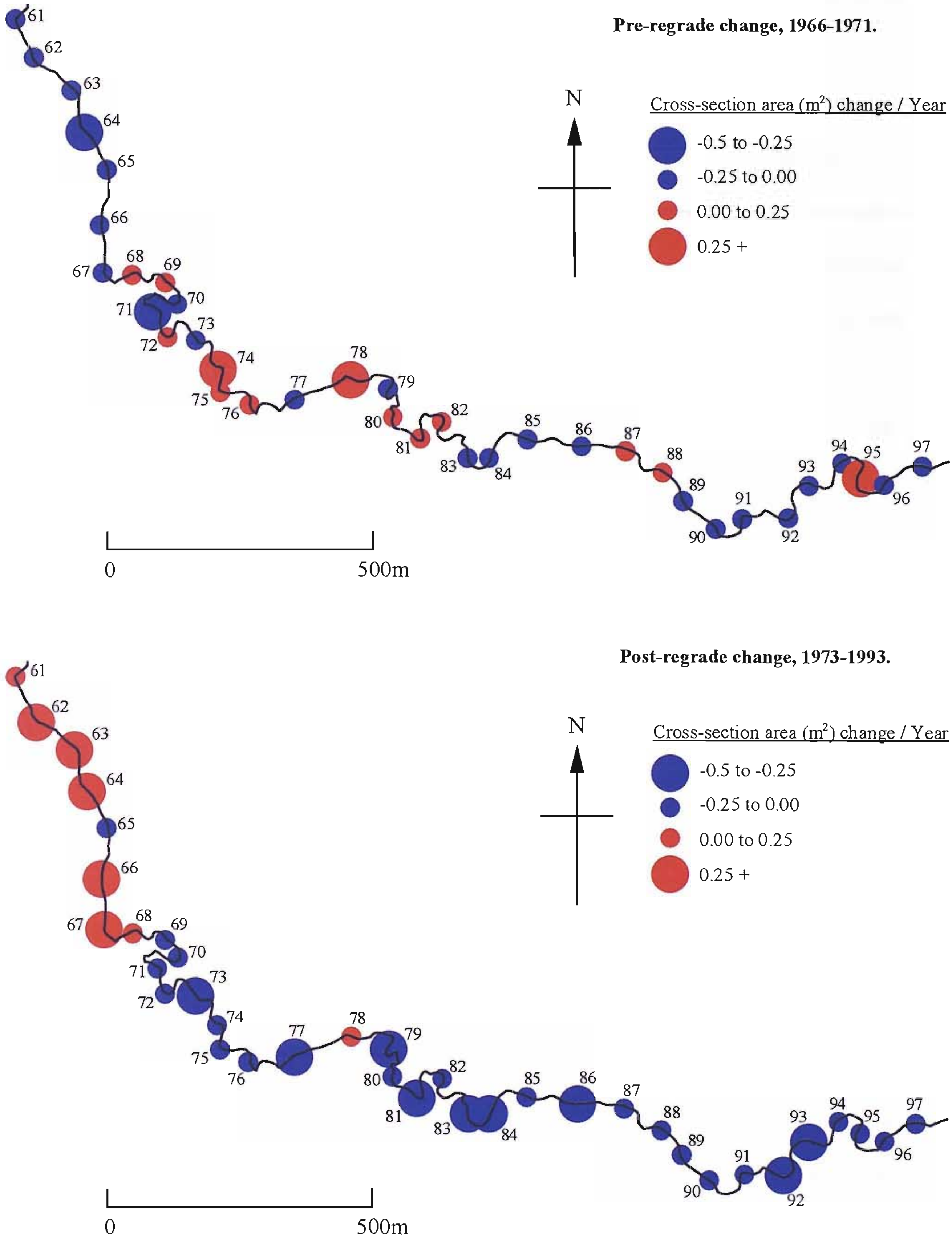


Figure 5.7 Examples of SPANS MAP outputs representing the spatial distribition of multiple attribute queries

The flexibility of the manipulation of the spatial data is the particular strength of the GIS-based approach. The ability to interact between several data sources (the planform record in combination with the cross-sectional data and the field data) allows the user to utilise the information to archive and display multi-faceted information in a multi-media format. For example, the potential of these approaches is explored in further detail in Chapter 8 where GIS based methods allow individual cross-sections to be scanned and stored digitally as attribute data. As a management tool this offers numerous possibilities, ultimately integrating not just the geomorphological information, but a whole range of other information on the river corridor.

5.4 ASSESSMENT OF ERRORS FROM CROSS-SECTION INFORMATION.

5.4.1 Introduction

As with the planform methodology described in Chapter 4, the results of the analysis are only as useful as the data quality. It is accepted that, as with planform information, these data can never be error free, but an understanding of the error and its variability is vital if the results of cross-sectional analyses are to be interpreted in a valid and meaningful way. In describing the stages of the methodology employed therefore, it is useful to address the limitations at each key stage. These errors, as with planform consist of two categories: inherent and operational errors. Inherent errors include those resulting from the collection and representation of cross-sectional values. Operational errors are those incorporated in the analytical methodology employed to interpret channel changes from the cross-sectional surveys. In a full description of an analytical methodology the assessment of error should be considered and evaluated through each stage of data transcription.

5.4.2 Inherent errors in cross-sectional data

Errors in the re-location of channel cross-sections in the field.

The planform record for the River Sence suggests that there has been no discernible planform adjustment over the 27 year period of the historical study. It seems reasonable to assume that a comparison of cross-sections relocated at specific sites within a study reach will provide a comparison of changes between surveys obtained at different dates and, indeed, Lawler (1993) suggests that cross sections should be marked out with pegs. Provided that the pegs themselves may be relocated in the field then the surveyor may be confident that the chosen site lies at the same location. However, this makes the assumption that there has been no planform displacement of the river channel between the two cross-section survey dates – either perpendicular to the flow or in a up/down-valley direction. Chapter 4 illustrates that the ability of the planform records to distinguish such lateral adjustments such as may be represented for the River Sence is diminished by the inability of the spatial resolution confidently to detect change. Therefore, just because the historical source information may suggest that there has been no lateral adjustment, this does not imply that there has been 'no' lateral adjustment.

Cross-sectional comparisons which seek precisely to re-locate the cross-section (e.g. by pegs, GPS etc.) therefore are attempting to define cross-sectional change in absolute space. Evidence from the experiment on the Highland Water and through experience from the River Sence would suggest that measurement in absolute space may potentially provide a misleading understanding of river channel stability and instability simply because the investigator may no longer be comparing like with like. Changes with cross-sectional analysis are likely to occur where lateral change in the channel boundary locations displaces the position of the cross-section such that the surveyed section may no longer cross at the same relative location or may no longer be perpendicular to the channel. In an extreme case, where a channel cut-off occurs, the cross-section may no longer exist as active channel. For example, a similar approach to re-locating cross-sections from 'non-pegged' historical evidence for the Canons Brook, Essex was used by Hollis and Luckett (1976) and Cox (1990), where position was identified from accompanying planform information. Cox (1990), when re-surveying Hollis' earlier sections, found it necessary to omit 8 sections due to insufficient planform evidence with which confidently to relocate them.

Cross-sectional comparisons are likely to be more realistic where cross-sectional measurements refer to relative space. In this case cross-sections will represent consistent channel planform characteristics. For example, re-location at meander apices and/or points of inflexion. In this way the comparison between temporal sequences of cross-sections will compare like with like.

However, when dealing retrospectively with cross-sectional information it is unlikely that repeat cross-sections will have been surveyed with this in mind. More likely is that the re-survey would have attempted simply to relocate the cross-section. On the basis of perception therefore the resultant locations may be inconsistent in absolute and relative space. For example, the meander apex may have migrated but the surveyor may still record the position of the apex.

Consequently a small re-location error upstream or downstream could lead to marked change in the recorded cross-sectional form of the channel. Natural changes in cross-sectional form may tend to have greatest variance over relatively small distances at meander bends, although, the relocation of cross-section is usually more reliable at meander bends, because the ability to fix the position of the cross-section with respect to the meander apex.

These challenges were highlighted in the collection of re-survey information in 1993. Re-location in the field was aided by taking bearings from the map sheet to grid north and then taking bearings to fixed features in the surrounding landscape (e.g. electricity pylons) which were also indicated on the accompanying basemap. It is estimated that the maximum error in the re-location of channel cross-sections from their cartographic representation was of the order of 5m for the 1993 re-survey of the River Sence. A 5m difference may give a very different impression of cross-sectional form. For example, bedform characteristics may change dramatically over this distance (e.g. from a pool to a riffle).

It is also important to note that there is no information to suggest that the location of the 1971 survey (and subsequent 1973 design survey which precisely replicates the 1971 cross-sections) should be any more or less accurate in relocating the 1966 cross-sections.

Errors in the cross-sectional survey

Unlike the boundary representation on the map, the cross-section typically provides the investigator with individual points depicting cross-sectional form. The concept that the surveyor's perception may mis-represent the continuous boundary condition is removed in that the plane of the cross-section is normal to the planform. Spatial accuracy is therefore a function of the generalisation employed to represent the cross-sectional form. Generalisation arises from instrumental errors (the operational precision of the equipment used to undertake the survey) and the systematic error of the surveyor and the investigator. For example, there is no implication that the more the number of individual survey points the greater the spatial accuracy of the cross-section, but rather the efficiency of these points to represent space without redundancy to a required level of generalisation.

As with planform errors, errors in the measurement of cross-sectional form may be gross, instrumental and systematic. It must be assumed that the introduction of gross errors (major survey mistakes) is minimal, since they would become apparent when the cross-sections are drawn and may then be corroborated with field evidence or, in the absence of corroboration then the survey point or entire cross-section can be omitted from the analysis. Instrumental errors are those errors introduced as a product of the apparatus used to obtain the measurements of cross-sectional form. While it is unlikely that the survey instrumentation used between dates will be the same, it is fair to assume that the working 'precision' of these instruments will far exceed the surveyor's ability to delimit breaks of slope and interpret channel boundaries. For example, the equipment used in the 1993 re-survey could de-limit vertical changes to within a tolerance of 5mm over a distance of 20m. The ability of the surveyor in these instances to detect vertical changes in the topography of the section is unlikely to ever be as subtle as 5mm, especially given variable seasonal vegetation cover which may obscure certain forms.

The most likely source of significant error in the measurement of cross-sections is systematic error introduced by the surveyor's perception in the determination of the cross-sectional form. For the 1966 and 1971 cross-sectional surveys data points are recorded across the floodplain extending approximately 10 - 20m either side of the river channel. Measurements are recorded in imperial units to the nearest 3 inches (77mm) horizontally and 1.5 inches (38mm) vertically. It may be argued that at this chosen resolution the ability to represent subtle breaks of slope which may be geomorphologically significant would be diminished. However, given the adoption of this constant working error then this should not seriously influence the overall estimate of channel form. Surveyor error is likely to be greater by virtue of the surveyor's perceptions of the existence and positions of breaks of slope across the section. Experience in conducting the 1993 re-survey indicated that to assume a bank-top level on the basis of topography, by taking a maximum upper break of slope (as represented by a vegetation limit, or having apparently reached an arbitrary vertical limit) is often misleading and that, upon plotting the cross-sectional form from the data, these visually estimated perceptions of the upper break of slope to the floodplain level may vary by anything up to 0.5m between the two opposing banks. It is therefore, preferable to extend the horizontal limits of each cross-section well beyond the immediate channel into the floodplain as was the case with the 1966 and 1971 surveys.

Estimation of the locations of breaks of slope across channel banks is also significant, especially given that different surveyors (typically without a geomorphological background) will have different perceptions of how to best represent the cross-sectional form. Field observation on the River Sence (and indeed all of the river-channels considered in this thesis) have demonstrated that seasonal vegetation coverage further compounds the surveyor's ability to perceive a break of slope. For example, Plate 5.1 shows the appearance of a near continuously convex channel bank, whilst the cross-sectional form recorded in the winter delimits breaks of slope which are obscured in summer by dense vegetation (Plate 5.1). Both the 1966 and 1971 surveys were undertaken in the summer.

There is no clear rule for the appropriate horizontal spacing of survey points employed to obtain river-channel cross-sections. In the case of the River Sence, the method employed in the 1966 and 1971 surveys was repeated in order to ensure comparability. Thus unequal horizontal spacing was chosen and breaks of slope were identified and surveyed in the field. Lawler (1993) notes that this method is most effective in the description of channel profiles, which commonly have locally defined breaks of slope separated by small distances, which may be missed by an equal horizontal spacing approach. The detail generated by an equal spacing approach is dependent on resolution adopted. It may generalise important bank features, or increasingly involve the collection of several points over uniform slopes, so increasing the timescale required to complete the survey.

Plate 5.1 Dense summer bankside vegetation

Summer vegetation may obscure the visual definition of subtle breaks of slope.

5.4.3 Operational errors in the determination of cross-sections

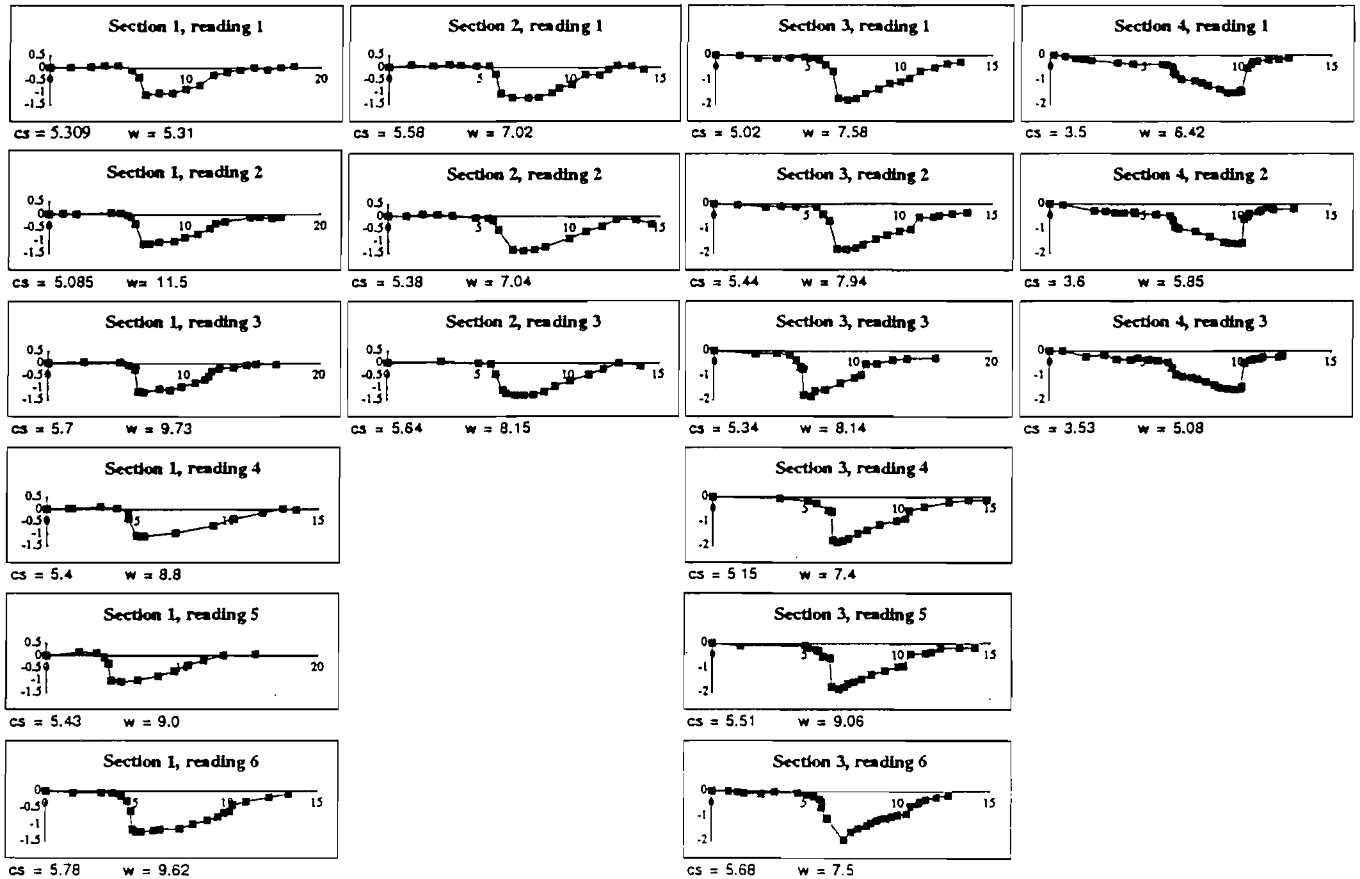
When quantitative indices are not required, manual overlay of tracings of cross-section form at a common horizontal and vertical scale and with respect to a common survey datum may be sufficient to identify and describe changes. If quantitative estimates of change are required two elements of error became increasingly important; the inherent errors in the source data, particularly those resulting from the surveyor's perception of features such as breaks of slope and the operational errors introduced as an attempt to make consistent comparisons between surveys at different dates. Estimate values may be extrapolated from the 1993 re-survey of the River Sence study reach and from the Highland Water experiment conducted by Downward (1995) and summarised in Figure 5.8. These indicate:

a) The estimation of bankfull channel width is the most sensitive of the channel variables to error in the location of survey points on the cross-section. For example, in the widest section, estimates of bankfull width vary between 8.8 and 11.5 m.

b) Estimates of Bankfull cross-sectional area are the least sensitive to surveyor error.

c) Distinct breaks in slope (e.g., at the boundary of an eroding, near-vertical bank) are surveyed with a higher level of confidence than those on gently-sloping eroding banks.

d) Survey of within-channel features are subject to greater error than bank and floodplain because of small variations in bed topography. This ability is a function of water depth and turbidity. Whilst such features may not contribute to variation in



cs = Bankfull cross-sectional area in m^2
w = Bankfull width in m

Figure 5.8 Estimates of channel form indices from repeated cross sectional survey from four cross-sections on the Highland Water, Hampshire

Four sections were surveyed by different pairs of surveyors working to identical guidelines. All pairs of surveyors used the same equipment. The variation in the representation of cross-sectional form arises as a consequence of systematic errors of perception precisely to delimit the cross-sectional form of the river channel.

the estimation of cross-sectional area, they may have significance in the determination of bankfull maximum depth.

e) Surveyors also had a varying ability to survey perpendicular to the channel. Thus, while the surveyors may be accurate in relocating the cross-section in the field, a small skewed displacement across the section, may result in different estimates being obtained for parameters of channel size and form. Again, width is the most sensitive variable to this source of error.

f) The ability to relocate the position of a cross-section from a map at 1:2500 scale varied +/- 5 metres up or down channel. In the case of the Highland Water the channel bedform (and by implication the representation of cross-sectional form) changes considerably over this distance (a maximum of 10m).

Temporal operational errors suffer the same challenges outlined for planform comparisons of river channel change. However, in the case of the River Sence cross-sectional information the survey dates are provided to the nearest day. In this respect, such errors may be considered negligible. However, the investigator must give specific attention to the nature of the channel change that occurs between successive surveys. For example, cross-sectional records for the River Sence are capable of discriminating bedform features that may be very transitory in nature, perhaps features which will demonstrate seasonal adjustment in accordance to variable flows and/or vegetation characteristics. The change in the cross-sectional form may provide the impression that the cross-section is unstable given the recorded difference in cross-section form between records, when in fact the channel is in a condition of dynamic equilibrium. In this sense, therefore, the spatial resolution is sufficient to discriminate channel form, but the temporal resolution may only be sufficient to extrapolate net change for the period between records. In the absence of corroborating evidence the significance of the observed cross-sectional change must be placed in perspective.

5.4.4 The assessment of total error

Figure 5.9 represents the transcription of information from their collection to the interpretation of the results of analysis. Cross-section analysis errors are almost entirely based around perception; perception of the surveyor to record the cross-section form in the field and of the user to determine a consistent datum level for comparison between cross-sections. Whilst the method developed here attempts to standardise data handling through the consistent definition of bankfull and data collection through the recommendation of a consistent survey methodology this is not sufficient to quantify a total error estimate.

This is compounded further in that the resolution of the cross-section varies spatially and perceptually. When we employ planform information the resolution or scale is essentially fixed across the sheet. This would be the case were the cross-sections to be represented merely as plots from which the user must interpret the form (in such cases the horizontal and vertical scales may be dis-proportionate to aid visual interpretation). However in many cases, as with the information for the River Sence the information is provided in terms of the individually surveyed co-ordinates. In this case the 'scale' of representation is based upon the separation of these co-ordinates. Thus, whereas Total Mapping Error estimates may be concluded in Chapter 4 because they are scale dependent, the inherent lack of dependency of scale

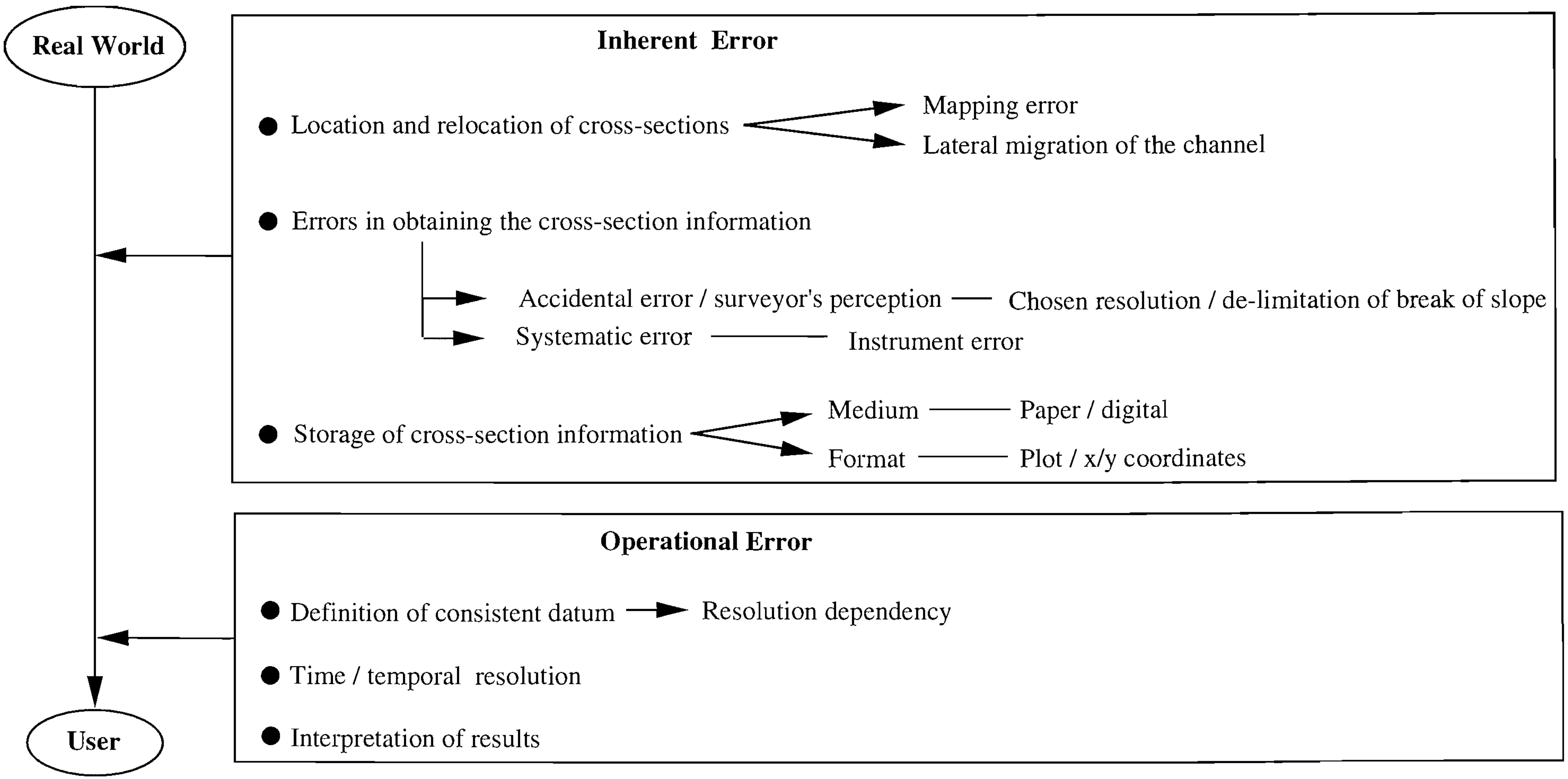


Figure 5.9 The transcription of topographical errors associated with cross-sectional information

(in any absolute terms) with cross-section data makes quantitative estimation of total error somewhat difficult to conceptualise. Rather the interpretation must be made subject to the systematic interpretation of the possible individual inherent and operational errors.

5.5 IMPLICATIONS AND RIVER CHANNEL CHANGE ON THE RIVER SENCE, 1966-1993

5.5.1 Introduction

This section describes the channel changes observed for the River Sence for the period 1966 - 1993. This section is sub-divided. Firstly, the changes in the individually measured parameters are considered and changing channel dimensions over the period are described. Secondly, the geomorphological interpretation of this information is developed by involving contemporary field evidence to infer channel processes and to reconstruct the development of the study reach over the period encompassing the pre and post regrade.

5.5.2 Changes in the estimated parameters

Better indications of the nature of the individual cross-section changes are obtained by considering the spatial distribution of channel change statistics and then interpreting them within the context of contemporary field evidence.

Bankfull indices representing cross-sectional changes observed between 1966 and 1993 are presented in Table 5.1 and Figure 5.10.

Changes in the bankfull cross-sectional area

Mean values for the study reach as a whole indicate low natural adjustment over the period 1966 to 1971, a large increase in cross-section area at regrade, and recovery through sedimentation of the channel in the period 1973 to 1993, with the exception of the lower part of the reach downstream of the Countesthorpe tributary.

Changes in the period 1966 to 1971 represent the pre-regrade variations. Mean cross-sectional values at both dates show little difference at $8.4m^2$. There is a wide variability in cross-section area through the study reach with a range of $4.8m^2$ to $14m^2$. A downstream increase in cross-section area from Kilby Bridge to Crow Mill might be expected, especially given the impact of the discharge input from the Countesthorpe tributary between sections 67 and 68.

The 1973 regrade dramatically alters the bankfull cross-section area of the channel in two principle ways. There is a large increase in the mean cross-sectional area of the channel as a whole, and the natural variability in the channel size is removed such that the range in cross-section area estimates demonstrates a reduced standard deviation. The spatial distribution of estimates of bankfull cross-section area changes from 1971 to 1973, therefore, mainly reflect the variation in bankfull cross-section area of the pre-regrade (1971) channel.

Section Number	Bankfull cross-section area change, m2				Bankfull width change, m				Bankfull depth change, m			
	66-71	66-71/a	73-93	73-93/a	66-71	66-71/a	73-93	73-93/a	66-71	66-71/a	73-93	73-93/a
61	-0.18	-0.04	4.46	0.22	0.00	0.00	2.26	0.12	0.00	0.00	1.83	0.09
62	-0.43	-0.09	5.30	0.26	0.00	0.00	3.49	0.17	0.01	0.00	1.42	0.07
63	-0.78	-0.16	6.69	0.33	0.00	0.00	4.69	0.28	-0.05	-0.01	0.66	0.03
64	-1.56	-0.31	5.98	0.30	0.00	0.00	3.30	0.17	-0.05	-0.01	1.38	0.07
65	-0.68	-0.14	-0.36	-0.02	0.00	0.00	0.56	0.08	0.00	0.00	0.27	0.01
66	-0.89	-0.18	7.32	0.37	0.00	0.00	3.34	0.22	0.01	0.00	0.80	0.04
67	-0.23	-0.05	5.35	0.27	0.00	0.00	4.36	0.22	0.00	0.00	0.53	0.03
68	0.00	0.00	2.83	0.14	0.00	0.00	3.90	0.20	0.01	0.00	0.93	0.05
69	0.71	0.14	-0.15	-0.01	1.76	0.35	1.60	0.16	0.00	0.00	0.76	0.04
70	-0.45	-0.09	*	*	0.00	0.00	*	*	-0.20	-0.04	*	*
71	-1.46	-0.29	-2.88	-0.14	0.00	0.00	1.27	0.11	0.08	0.02	-0.09	0.00
72	0.71	0.14	-0.17	-0.01	0.60	0.12	2.41	0.03	0.00	0.00	0.43	0.02
73	-0.67	-0.13	-5.62	-0.28	0.00	0.00	0.35	0.01	0.00	0.00	0.31	0.02
74	3.61	0.72	-0.94	-0.05	0.32	0.06	1.00	0.07	0.65	0.13	0.41	0.02
75	0.00	0.00	-3.72	-0.19	0.00	0.00	0.10	0.01	0.01	0.00	0.04	0.00
76	0.00	0.00	*	*	0.00	0.00	-0.30	-0.02	0.25	0.05	0.13	0.01
77	-0.35	-0.07	-5.83	-0.29	0.00	0.00	0.00	0.01	-0.10	-0.02	0.22	0.01
78	2.29	0.46	0.90	0.05	0.00	0.00	0.10	0.01	0.00	0.00	0.34	0.02
79	-0.19	-0.04	-6.73	-0.34	0.00	0.00	0.19	0.07	0.00	0.00	-0.31	-0.02
80	0.00	0.00	-3.01	-0.15	0.00	0.00	-0.19	0.01	0.00	0.00	0.37	0.02
81	0.00	0.00	-5.87	-0.29	0.00	0.00	-0.30	-0.02	0.00	0.00	-0.17	-0.01
82	0.00	0.00	-2.42	-0.12	0.00	0.00	0.69	0.05	0.00	0.00	0.20	0.01
83	-0.20	-0.04	-5.23	-0.26	0.00	0.00	0.13	0.04	0.00	0.00	0.09	0.00
84	-0.59	-0.12	-5.09	-0.25	0.00	0.00	0.67	0.06	-0.05	-0.01	-0.14	-0.01
85	-0.41	-0.08	-4.19	-0.21	0.00	0.00	0.33	0.02	0.00	0.00	0.02	0.00
86	*	*	-5.17	-0.26	*	*	0.45	0.54	-0.15	-0.03	0.28	0.01
87	0.04	0.01	*	*	0.96	0.19	-2.16	-0.04	0.00	0.00	0.15	0.01

Table 5.1 River Sence cross-sectional change data

88		-4.17	-0.83	-4.43	-0.22	0.00	0.00	-0.26	-0.01	-0.64	-0.13	0.18	0.01
89		-0.71	-0.14	-1.31	-0.07	0.00	0.00	-0.79	-0.04	0.70	0.14	-0.57	-0.03
90		-1.14	-0.23	-3.01	-0.15	0.00	0.00	0.60	0.03	-0.26	-0.05	-0.74	-0.04
91		*	*	*	0.00	*	*	*	*	0.00	0.00	0.11	0.01
92		*	*	-5.50	-0.28	*	*	0.49	0.15	0.03	0.01	-0.04	0.00
93		-0.01	0.00	-7.67	-0.38	-0.07	-0.01	0.55	0.08	0.00	0.00	-0.05	0.00
94		-0.16	-0.03			0.00	0.00	-0.50	-0.02	0.00	0.00	0.11	0.01
95		2.27	0.45	-2.37	-0.12	0.00	0.00	1.49	0.08	0.01	0.00	-0.15	-0.01
96		-0.07	-0.01	-1.89	-0.09	0.00	0.00	0.00	0.04	0.00	0.00	0.24	0.01
97		-0.21	*	*	*	0.00	0.00	0.20	0.01	-0.03	-0.01	0.09	0.00
Kilby-CTC	**Mean**	**-0.04**	**-0.01**	**-3.31**	**-0.16**	**0.13**	**0.03**	**0.43**	**0.06**	**0.01**	**0.00**	**0.11**	**0.01**
	SD	0.75	0.16	2.11	0.11	0.23	0.05	0.71	0.07	0.11	0.02	0.24	0.01
CTC-Crow	**Mean**	**-0.68**	**-0.14**	**4.96**	**0.25**	**0.00**	**0.00**	**3.14**	**0.18**	**-0.01**	**0.00**	**0.98**	**0.05**
	SD	0.34	0.07	1.66	0.08	0.00	0.00	0.99	0.05	0.02	0.00	0.48	0.02
Total	**Mean**	**-0.17**	**-0.03**	**-1.44**	**-0.07**	**0.11**	**0.02**	**0.97**	**0.08**	**0.01**	**0.00**	**0.28**	**0.01**
	SD	0.71	0.15	3.53	0.17	0.19	0.04	1.23	0.08	0.09	0.02	0.36	0.02

* Missing data   CTC, Countesthore confluence

Table 5.1 (Continued) River Sence cross-sectional change data

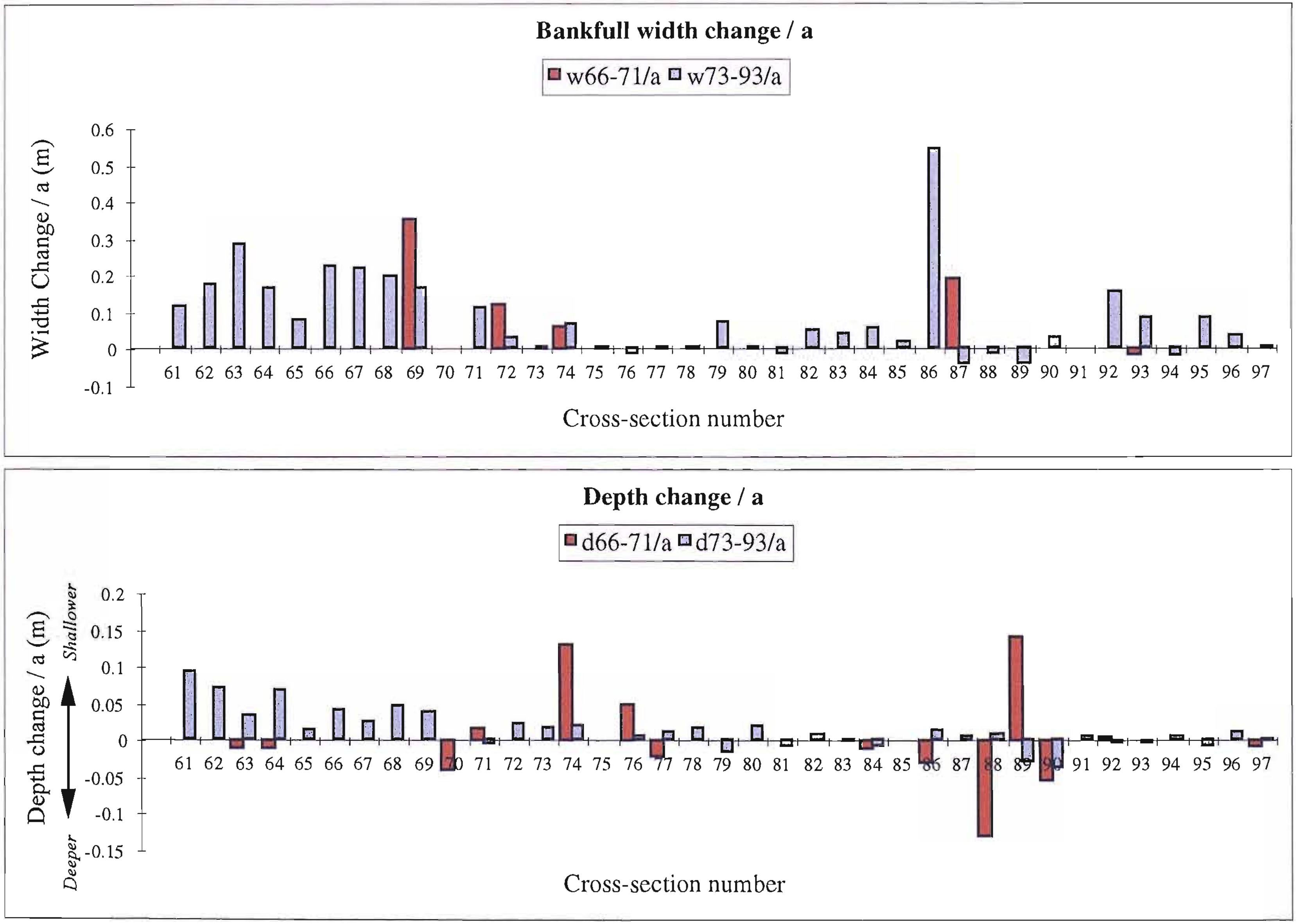


Figure 5.10 Example graphical representation of net cross-sectional changes by section on the River Sence pre-regrade (1966-1971) and post regrade (1973-1993)

Bankfull cross-section area change in the period 1973 to 1993 represents a channel capacity reduction as a result of geomorphic recovery from the regrade. The channel may be divided into two broad zones reflecting the nature and magnitude of post-regrade channel maintenance from 1989. In the reach immediately downstream of the Countesthorpe Brook confluence, the channel's cross-section area has doubled from its pre-regrade 1966 and 1971 values, reflecting comprehensive re-sectioning and minimal recovery. In the reach from Kilby Bridge to the Countesthorpe Brook confluence the cross-section area of the channel is only fractionally higher than the pre-regrade (1971) channel, indicating near complete recovery of bankfull cross-sectional area to the regrade through net deposition within the reach.

Bankfull width change.

Bankfull width change is minimal throughout the period 1966 to 1993 with the exception of the reach immediately downstream of the confluence with the Countesthorpe Brook confluence. Mean pre-regrade channel bankfull width (1966-1971) is identical at 9.2m, the 1973 regrade did little to effect the bankfull width. The affect of the regrade was to produce a trapezoidal section within the existing channel width such that the mean regrade channel bankfull width is largely unaltered from the pre-regrade channel width of 9.5m. Post-regrade change (as with cross-section area) may be divided into two distinct zones divided at the Countesthorpe Brook confluence. From Kilby Bridge to the Countesthorpe Brook confluence the channel width increased on average by 0.5m (an increase of about 5%) downstream of the confluence there was an average increase of approximately 3m (an increase of about 30%).

Bankfull depth change

Pre-regrade bankfull depths show little change in the period 1966 to 1971 with mean values nearly identical at 1.7m. The effect of the 1973 regrade was to increase the overall channel depth on average by 0.25m and remove much of the site to site variation. Regrading work also had the effect of totally removing the bed topography of the channel, such that estimates are uniform, demonstrating minimal variation with a low standard deviation.

Estimates of bankfull maximum depth demonstrate a recovery from 1973 to 1993. The mean bankfull depth of the channel upstream of the Countesthorpe Brook tributary has also demonstrated a further mean bankfull maximum depth increase from the pre-regrade estimate (although to a lesser extent than downstream) and a return of the slope profile to the pre-regrade estimates. Bankfull maximum depth increases may be explained by post 1989 channel maintenance intended to alleviate bed sedimentation. Hydraulics Research (1990) notes that the 1989 routine maintenance dredged the channel bed at the low flow width limit by approximately 0.5m.

5.5.3 Geomorphological interpretation

The observations from the quantitative analysis of the estimated parameters record the changes in channel form for the period 1966 to 1993. These values describe the net change at each section and their spatial distribution can be displayed using SPANS MAP. This section considers the historical information with contemporary field evidence to reconstruct the historical geomorphological development of the channel from 1966.

The pre-regrade channel: 1966 to 1971

The period from 1966 to 1971 represents the natural regime channel, demonstrating only minimal variations in the channel form which exhibit no obvious spatial trend. Sear (1993) notes that channel maintenance prior to the regrade scheme was minimal, consisting mainly of routine shoal removal. Thus, changes in the channel between 1966 and 1971 may be considered to represent 'naturalised' adjustment responding to yearly variation in flow and sediment transport. With the exception of routine shoal removal it is proposed that the sediment budget of the reach is in balance and there are no clearly defined zones of erosion or deposition. As such the reach is considered to be geomorphologically stable in a state of equilibrium.

The regrade channel

The regrade produced a spatially uniform trapezoidal cross-sectioned channel (channel planform was largely unaltered). The 1973 design regrade channel effectively destroyed all natural variations in cross-sectional channel form. Pool and riffle sequences were obliterated and were replaced by a uniform bed profile. Channel banks indicate greatly increased vertical angle and height increasing the potential for geomorphological instability.

The post regrade channel, 1973 to 1993

The artificially modified geometry of the study reach of the River Sence has had significant bearing upon the channel changes that have occurred in the period 1973-1993. It must be remembered that human-induced stimuli promoting channel change may be experienced at catchment scale and not necessarily confined to the study reach, but effect the discharge and sediment regime of this reach.

Where the channel has been largely undisturbed by post-regrade operations, the channel has demonstrated widespread recovery to cross-sectional dimensions similar in magnitude to those of the pre-regrade channel. This recovery indicates net deposition over the 20 year period. Downstream of the Countesthorpe Brook confluence, the sections show little evidence of recovery, in fact the reverse is experienced with all sections showing enlargement of their cross-section form. This has been due to channel maintenance (from 1989) which has been responsible for reworking the channel at these sites.

The most obvious spatial change in channel morphology occurs up and downstream of the Countesthorpe Brook confluence. Upstream of the Countesthorpe Brook confluence, post regrade maintenance has been minimal involving only dredging of sediment from the low flow. As a result, the channel displays a typically deeper bankfull depth than before the regrade but, the cross-sectional area typically shows geomorphological recovery to approach the pre-regrade values of 1966 and 1971. Whilst this upstream reach may collectively be considered to have returned to a pre-regrade form, the field evidence clearly indicates that there is a sedimentary imbalance perpetuated by continued maintenance. Sediment supply to the reach is abnormally high due to continuing upstream channel working (e.g. regrading at Great Glen, 1993/1994) which has led to increased sediment supply to the reach. Therefore while estimates of channel form 1973-1993 indicate overall recovery to 1971 estimates, closer examination of the data and field evidence demonstrates that a stable equilibrium channel form is not achieved while net rates of erosion and deposition approximate the pre-regrade estimates, gross rates of erosion and deposition (reflected in the standard deviation of estimates) have increased.

The reach upstream of the Countesthorpe Brook confluence shows morphological diversity. The localised adjustment of individual short reaches is based on the recent response of the channel which appears to reflect localised land-use and channel management practices.

Certain cross-sections exhibit increased bank erosion which is believed to be the result of unrestricted cattle access to the southern channel bank or where wire fencing is in bad repair and the cattle can graze through the fencing to the banktop. It is believed that the effect of livestock poaching has two major effects; bank stability is affected by cattle trampling causing direct erosion, and, cattle grazing removes the biomass and root structures of plants which would otherwise stabilise the banks and stunts vegetation succession. In individual locations where there is continuous fencing, the cattle have access to the river channel for water. At these locations the channel banks are completely devoid of vegetation and are uniformly graded to the water surface. Trimble (1994) observed that for experimental plots in Tennessee, unrestricted cattle access was responsible for erosion rates estimated at six times the values of restricted access sites.

5.5.4 Summary

Stability within the River Sence may be enhanced. A viable solution is through a combination of weed control and the maintenance of fencing and banktop vegetation to provide a livestock buffer. Then, allowing the channel to naturally adjust back to an equilibrium form in the absence of upstream modifications. As long as the regrade operations continue upstream of Kilby Bridge there will be a continuing imbalance of sediment load through the reach.

Excessive sedimentation may be controlled periodically by maintenance of the low flow width through the periodic removal of low flow vegetation. Excessive erosion is predominantly the result of over-steepened bank angles and their height, but as long as the low flow channel is maintained then this adjustment should stabilise naturally over time.

5.6 CONCLUSIONS

This chapter has addressed the challenge of investigating river channel change for a river channel for which changes occur largely 'within-channel'. In the absence of historical planform records at high spatial resolution (e.g. high-resolution aerial photography) alternative sources of historical information must be used to represent change. Within-channel changes may also occur with a temporal frequency that exceeds the temporal resolution of 'traditional' planform records to reliably depict the sequence of changes that occur.

The chapter has illustrated the value that a historical analysis using cross-section records may bring to a geomorphological investigation by considering the example of the River Sence, a river that has received considerable management attention in order to improve the river channel's capacity to convey flows and improve agricultural drainage. The nature of the river channel adjustments, witnessed for the study reach of the River Sence through management attention and contemporary geomorphological reconnaissance survey, associates well with the resolution that the cross-section records provide:

a) They have a closely associated spatial resolution - Individual cross-section points are able to describe within-channel features to an accuracy of 5mm provided these features may be identified in-situ.

b) They have a closely associated temporal resolution - The cross-sectional record spans the period of human induced modification (the River Sence Improvement Scheme) and record channel form at key stages in the river channel history, defined here with respect to the channel works.

The chapter has considered the accuracy of the approach by considering the transcription of errors from original cross-section survey's through to analysis and interpretation of the results. Unlike historical planform information, historical cross-sectional information is not bound by the same conventions of scale of representation. For this reason, the suitability of the cross-sectional record to confidently fulfil the requirements of the investigation must be made through the systematic interpolation of the inherent errors of the survey information and the operational errors introduced through their analysis. The methodology does not provide the facility to provide a quantitative estimate of Total Error but rather its key contribution to applied geomorphological research is to empower the investigator to consider the relative significance of the individual component errors and their reletive accuracy in identifying within-channel features with confidence.

5.7 SUMMARY

a) The accuracy of the interpretation is improved where individual cross-section survey points are located with a low position error as a consequence of survey methodology. Position error is a function of instrumental error and the surveyor's perceptual abilities to interpret river channel cross-sectional form. For example, surveyor error in the estimation of the same cross-section bankfull width on the Highland Water was found to vary by up to approximately 30% between different surveyors using identical equipment.

b) The smaller the spacing between individual cross-section survey points (and by implication, the greater the number of cross-sectional points per given cross-section) the greater the ability of the survey to represent cross-sectional form.

c) The investigation must be clear as to whether the cross-section survey represents the river in relative space (e.g. repeat cross-sections represent channel transects with respect to morphological planform variables such as the meander apex or point of inflexion) or in absolute space (e.g. repeat cross-sections represent channel transects at fixed points relative to the floodplain). In both cases, the interpretation must consider the position accuracy of individual transects.

Through the worked example for the River Sence, guidelines have been recommended for the analysis of cross-sectional form and the interpretation of errors. Interpretation of change was found to be more meaningful where the cross-section record could be linked to other forms of geomorphological data, be this historical planform information or contemporary field evidence. The chapter has demonstrated that by adopting a GIS based approach (linking the spatial planform information to the attribute data derived from the channel cross-section statistics) proved to be a useful and versatile means by which to archive, analyse and model the information.

CHAPTER 6

THE EXTRAPOLATION OF RIVER CHANNEL CHANGE FROM HISTORICAL GROUND-BASED PHOTOGRAPHS: THE RIVER TILLINGBOURNE, SURREY.

6.1 INTRODUCTION

Many quantitative studies of historical river channel change have investigated rivers for which change may be estimated through the analysis of planform and/or cross-sectional information determined from topographic records such as historical maps, airborne imagery and engineers' cross-sections. The ability of the historical record to delimit the nature and magnitude of river channel adjustment from planform and cross-sectional records has provided an invaluable asset to assessing change and promoting geomorphological contributions to river channel management. However, this thesis has demonstrated that there are limitations to which these sources of information may yield reliable results because as the scale of channel adjustment becomes smaller and increasingly subtle so the ability of these methods to estimate indices of change with confidence decreases. In these cases, historical sources of information may well be available, but may not necessarily be the most appropriate with which reliably to determine channel change. For example, an urban river channel may exhibit no discernible planform adjustment and may have only limited available cross-section information, perhaps at one date only in the past or for a very limited reach of the watercourse. However, the river may still be experiencing change which is cause for management concern such as localised bank failure and/or within-channel sedimentation. Geomorphologically sensitive management solutions seeking to enhance the geomorphological diversity of the river channel, in the absence of complete sequences of historical information, are reliant on decisions based on contemporary observation and modelling.

However, in many cases, the concept of restoration of naturalised conditions must recognise that complete, or even partial, return to a pre-disturbance condition may be inappropriate. Considerable changes to the watercourse and the catchment (e.g. encroachment to banktop, dislocation between watercourse and floodplain, flow and sediment regulation etc.) have meant that it would be totally unrealistic ever to hope to restore the river channel to a 'natural' condition as might be perceived in the river's history. Yet, there may still remain considerable opportunity to rehabilitate and enhance river channel characteristics within the imposed limiting constraints. In this way, geomorphologically sensitive approaches may attempt to 'tend towards' natural conditions. In this instance, the historical record, however fragmented or limited in terms of its ability to provide quantitative indices of adjustment, might prove invaluable as a means by which the geomorphologist may produce a qualitative 'impression' of the past in order to draw analogies for the future.

In this sense the river channel change questions may not necessarily demand that the accuracy of these sources of information necessarily be so rigidly defined as might be required in a quantitative analysis. As such, the analysis may draw on a range of historical sources in a range of formats which might otherwise have been ignored.

This chapter aims to provide a methodology for extrapolating a semi-quantitative interpretation of river channel change based on ground-based oblique historical photographs. The chapter considers the case of the River Tillingbourne, Surrey, as an example of a stream, typical of many in south-eastern England, for which there has been a long and complex history of human influence. Rivers such as the Tillingbourne, by virtue of their rural setting, may typically be perceived as 'natural' but may owe their form and morphology to many hundreds of years of human interaction. Unlike their urban counterparts, where the impact of 20th Century engineering modification may obliterate earlier human adjustments, many small lowland rural catchments in south-east England still retain the imprint of human modifications which may be traced back centuries. Examples include fisheries, water meadow diversion and, perhaps the most significant in the case of the River Tillingbourne and many similar river channels in south-east England, for milling. The specific objectives of this chapter are as follows:

a) Introduce the River Tillingbourne study site and the contemporary challenges to management.

b) Presentation of a semi-quantitative methodology for assessing river channel change based on contemporary survey supported by historical ground based photographs.

c) Determine the accuracy of the results based on as assessment of the errors associated with the methodology.

d) Assessment of the significance of the results for developing an enhanced historical awareness of river channel change as an aid to making geomorphologically sensitive river channel change decisions.

6.2 THE STUDY SITE: THE RIVER TILLINGBOURNE, SURREY

6.2.1 Rationale for the choice of study site

The River Tillingbourne study site was chosen because it has a long history of human intervention for which more 'conventional' historical information, such as planform and cross-sectional records, are unsuitable as a means of extrapolating river channel change. The historic planform information has insufficient resolution to yield detailed channel change indices because of the river's size and lack of planform adjustment. Extended tree-lined sections of the river channel obscure the channel from aerial view making the use of aerial photographs inappropriate. Cross-sectional records were not available. However, field evidence and evidence offered through discussion with river channel managers demonstrates that the river exhibits variable degrees of adjustment which have prompted channel work (Environment Agency, Pers. Comm.). Furthermore, there is an extensive historical record available for the River Tillingbourne in the form of historical ground-based photographs, drawings and written accounts that may be readily addressed.

6.2.2 A background to the River Tillingbourne and the impact of mills

The River Tillingbourne

The River Tillingbourne is a tributary of the River Wey, flowing westwards to the confluence with the River Wey at Shalford, Surrey (Figure 6.1). The river occupies a valley on the North Downs at the northern limb of the Wealden anticline. The eastern tributary rises on the Northern slopes of Leith Hill (the highest point on the

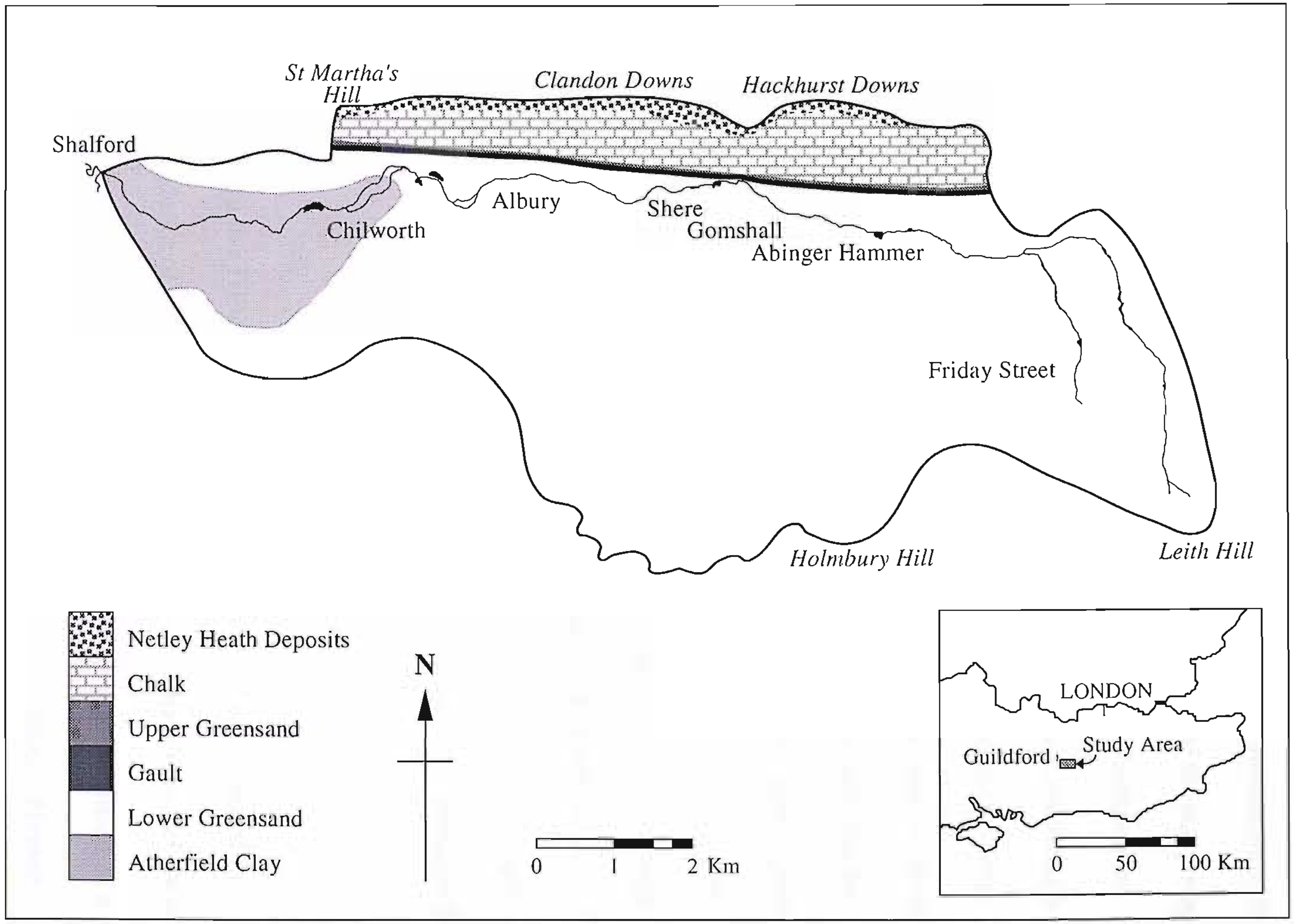


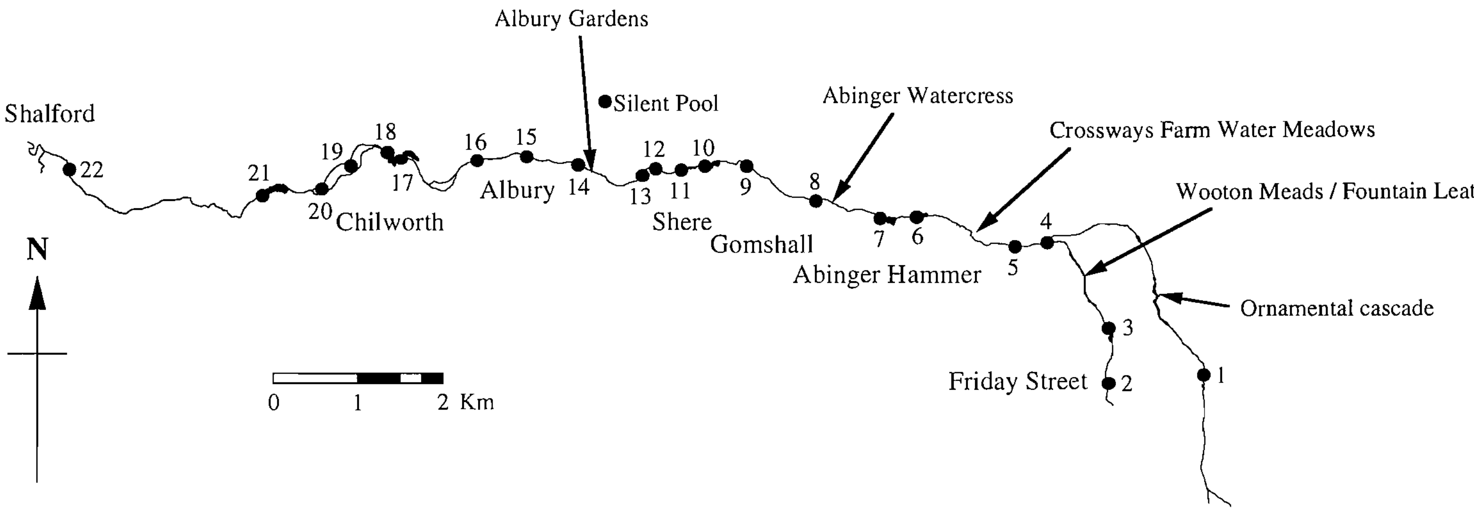
Figure 6.1 River Tillingbourne catchment location and solid geology

North Downs) and other main tributaries include the Friday Street Branch, Sutton Stream and the Law Brook. The main river channel drains westwards on Lower Greensands confined by the Chalk scarp ridge of the North Downs. The channel flows within the Hythe beds of the Lower Greensands comprising sandstone with beds of Chert. Local head deposits derived from the solifluction of the scarp slope yield clays derived from the Gault and Upper Greensand boundary between the Lower Greensands and Chalk. These conditions combine to provide moderately cohesive sediment locally armoured with Chert. Numerous spring-lines emerge along this Chalk ridge (e.g. at Silent Pool) and these intermittently feed the River Tillingbourne. In the lower course, west of Chilworth, the channel cuts into the Atherfield Clay deposits, however, the upper boundary to the Hythe beds is poorly defined such that there is a gradual transition to the clay substrate (Gallois, 1965; Gibbons, 1981). Average discharges of the River Tillingbourne are in the range of 0.5 - 0.7 Cumecs. Discharge rarely exceeds 1 Cumec and seldom falls below 0.3 Cumecs. A perennial baseflow component indicates the channel's ability to provide a constant source of power for the many mills that depended upon the constant flow of water it provides.

Historical changes in the Tillingbourne Valley have been well documented for centuries, with evidence of human settlement pre-dating the Doomsday survey of 1086. The waters of the River Tillingbourne have historically been utilised as a source of power, water supply, for waste disposal and ornamentation. Human settlement in the Tillingbourne valley reflects the importance of the river, with villages and communications following the east-west axis of the valley. As such the geography of settlement and industrial development of the valley is inextricably linked to the river.

The density of mills along the main river-channel and tributaries is high, with over 20 mill sites having been recorded in total for the 19km length of main channel. Mills served a variety of uses, water power being used for milling corn, paper making, fulling, metal working, tanning and gunpowder production. The history of the individual mills has been well documented, evidence indicating that many of the mills continued to be used into the early 20th century. However today, those that remain have either fallen into disrepair, have been modified or have been renovated and preserved for their heritage value (Figure 6.2). Industrial development within the valley has also given rise to marked landscape change which has affected the floodplain environment. By the early 17th Century clear-felling and open grazing began a process of deforestation, which combined with a subsequent demand for wood fuel by the charcoal, iron, gunpowder, brass and copper industries lead to significant landscape changes (Surrey Industrial History Group, Pers. Comm.). Reforestation, which began in the 18th and 19th centuries, has contributed to the production of the contemporary landscape.

In addition the waters of the Tillingbourne have been important for two other main industries. Firstly, watercress farming centred mainly around Abinger Hammer and can be traced back to the last century when it was the first large-scale watercress enterprise in England and provided an important source of local employment. The coming of the railway in 1849 opened up markets in London and other major cities, and by 1888 watercress growing had extended as far as Chilworth (Miller, 1996). Secondly, the river provided a valuable resource as a fishery. Brandon (1984) notes that the water quality of the River Tillingboune has undergone a marked improvement into the 20th Century with the decline of the use of the River for



1.	Brookmill	TQ 139455	16th century mill (only pond remains).
2.	Pond bay	TQ 127451	Gunpowder mill. No mill remains.
3.	Friday Street	TQ 128458	Late 16th century corn mill. Closed 1736. Mill house and weir remain.
4.	Wooton wire works	TQ 120470	1627. Moved from house 1675 and river landscaped. Abandoned remains.
5.	Abinger Mill	TQ 110460	<1086-1890. Multiple uses. Mill demolished early 20th century. Landscaped.
6.	Abinger Hall Pump	TQ 105475	1803. Pumped water from well to Abinger Hall. Main house demolished 1959.
7.	Paddington Mill	TQ 100472	<1086. Multiple uses. Mill pond used for angling to 1965. Now completely silted.
8.	Abinger Forge Mill	TQ 095475	Iron working <1788. Converted (paper making, corn). Factory on old site.
9.	Gomshall Mill	TQ 085478	<1086. Multiple uses. Recent renovation (inoperative) - restaurant and shops.
10.	Netley Mill	TQ 079479	<1233-1907. Multiple uses. Pump house 1903-1952. Reclamation of mill pond 1970.
11.	Shere Lower Mill	TQ 076479	<1086. No mill remains.
12.	Pumphouse	TQ 072478	Water powered pumphouse 1890- early 20th century. House conversion
13.	Shere West Mill	TQ 068476	Corn mill <1638. Pond restoration (aesthetic and flood storage) early 1990's.
14.	Albury Park Mill	TQ 062479	<1727. Rebuilt, operational until 1820's. No mill remains.
15.	Albury Estate Pumps	TQ 044476	Water powered pump (well water to Albury) 19th century. Site now a trout fishery.
16.	Albury Mill	TQ 053479	<1255. Mill remains (inoperative), now site of laboratories.
17.	Postford Upper Mill	TQ 041480	Paper mill early 1800's, closed 1830's. Waterloo pond remains.
18.	Postford Lower Mill	TQ 039480	<1693. Multiple use. Site used (mill inoperative)<1991. 1996 housing redevelopment.
19-21.	Gunpowder Mills	Chilworth	<1086 corn milling. Gunpowder works to 1920. Abandonment.
22.	Shalford Mill	TQ 001476	<1086-1914. Mill pond siltation. Mill restored 1930's. Now managed by National Trust

Figure 6.2 The location and history of mills sited on the River Tillingbourne

industrial use and waste disposal. Today, the river is an important trout fishery, both with the creation of fish farms and the excavation of lakes for angling.

Land management in the Tillingboune Valley owes much to the continued role of estate ownership. Presently the two estates in the Tillingbourne valley are the Albury Estate in the mid-catchment and the Wotton Estate in the upper-catchment. The Estates have historically been responsible for the development of the River Tillingbourne with ownership of many of the mills and fisheries. Consequently, the function of any one individual mill could be integrated with adjacent mills to optimise the river resource without untoward mis-use of the river water to the detriment of other users. It is this closely integrated structure that allowed such diversity and density of river use to develop and flourish.

Both estates have used the river for ornamental purposes by landscaping gardens adjacent to the river-channel constructing ponds, waterfalls and fountains. For example, John Evelyn's work at the Wotton became one of the best known of the mid-17th Century Italian styled water-gardens in England. At Albury Gardens (on the Albury Estate) a landscape previously created by the diversion of streams and the building of dams for the purpose of milling became with a little reworking one of the earliest examples of landscape gardening.

The geomorphological impact of mills

Despite considerable literature considering the estimation of river-channel change as a consequence human-induced conditions there has been little by way of reference to the impact of mills and their associated structures upon a river's long-term morphology. Literature has tended to address geomorphological issues indirectly from a hydrological or engineering perspective or have adopted a biological perspective to watercourse impacts (e.g. Doeg and Koehn, 1994; Lewis, 1996; Mains-Smith and Treadgood, 1991; Thoms and Walker, 1992 and Walker *et al.,* 1991). This is surprising given that within the Thames catchment alone milling has historically represented a direct and extensive modification to many of the Thames tributaries. While many of the mills are no longer active and may have been modified and/or have fallen into disrepair, many of the associated channel modifications (weirs, sluices and mill channels) remain and may continue to influence the contemporary stability of the river.

Water mills usually require that the river channel be in some way artificially modified to promote the efficient operation of the mill. Typically, a weir is constructed artificially to raise the water level upstream of the mill creating a backwater effect to produce a constant head of water from which to generate power (Jansen *et al.*, 1979). Additional channels may be constructed to divert water from the upstream channel through controllable structures (e.g. sluices) to regulate the water stage contained upstream. The creation of a backwater may result in overbank flooding and the creation of a mill pond (Figure 6.3).

The construction of the weir and associated modification to the watercourse has a profound influence on the natural function of the river-channel. Many of the mills have passed into non-operational condition and have been subsequently modified or allowed to fall into disrepair. There is a clear case for investigating these rivers in order to estimate potential future changes given that the river channel may have long established geomorphologically stable rsponse to the imposed modifications. A

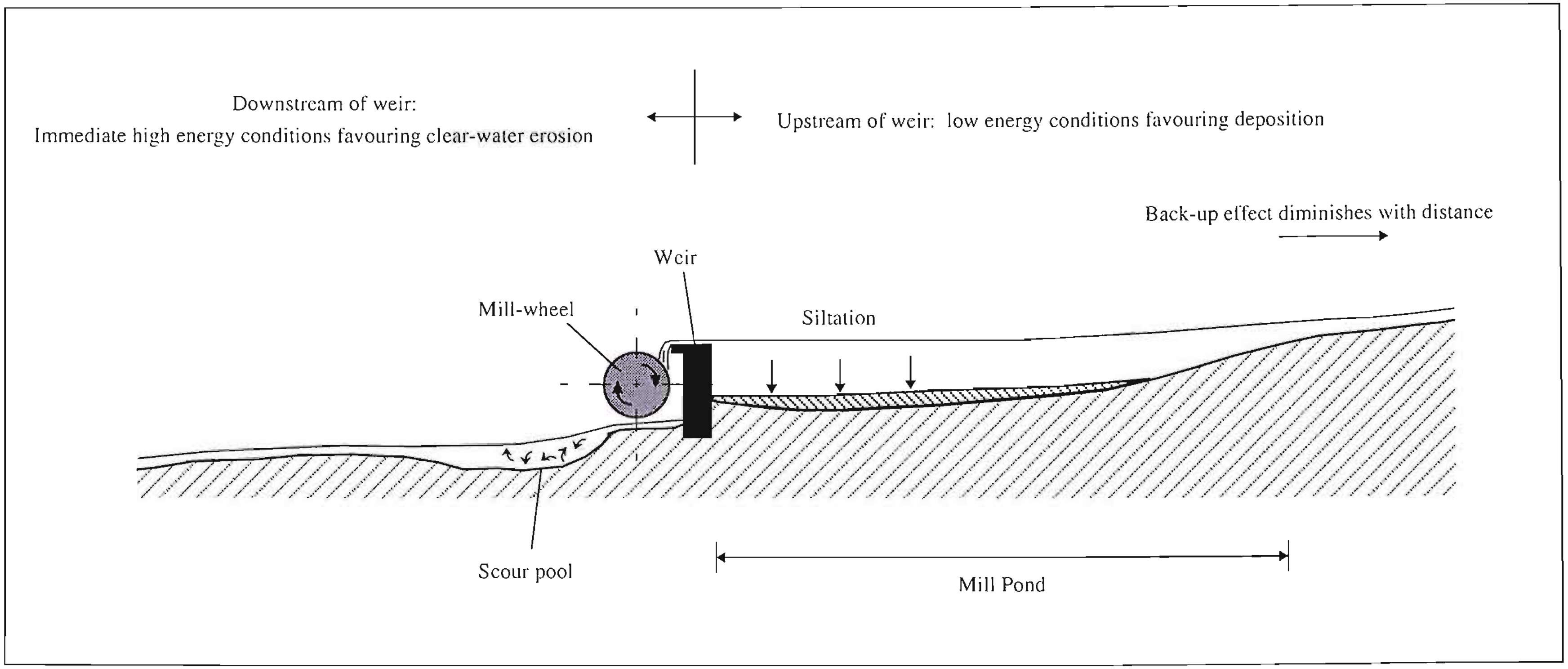


Figure 6.3 Diagrammatic long profile to illustrate the morphological impact of the mill

stable river-channel may be considered one in which the maintenance of equilibrium is achieved through a balance between the sediment supplied and the sediment carried through a given reach (Jaeggi, 1992). Mill construction promotes the adjustment of the long profile of the river in both upstream and downstream directions. The overall effect of a sequence of closely spaced mills (as was the case with the River Tillingbourne) was to change the natural longitudinal profile of the channel to one which is effectively stepped, the gradient broken by a sudden increase in gradient at the weir crest (Thoms and Walker, 1992). Upstream of the weir, the resulting reduction in gradient promotes a reduction in stream power and associated reduction in the river sediment carrying capacity. This reduction encourages the deposition of fines, promoting vertical aggradation. Immediately downstream of the weir, stream power is raised which, in combination with the reduction in sediment load may promote localised 'clear-water' erosion as the river attempts to recover sediment and re-establish equilibrium conditions. As with other examples of impounding river structures the effects of upstream aggradation and downstream aggradation decay with distance as the naturally occuring gradient is re-established. However, in the case of many rivers in southeast England, the close proximity of mills on the watercourse means that the river maintains an artificially determined long profile for the majority of its length.

The imposition of mills on the watercourse will therefore have had a profound influence upon the geomorphological stability and sediment transfer. The backwaters and mill ponds will provide a series of storage reservoirs which would effectively regulate flows (dependent on storage volume) reducing the annual occurrence of peak flows in the downstream channel. Furthermore, the near stationary waters of the mill ponds themselves act as sediment sinks, effectively disconnecting sediment throughput to all but fine suspended and dissolved sediments in sections between adjacent mills. Consequently, while flow conditions would favour increased sedimentation, active sediment must be derived locally and is therefore controlled mainly by localised conditions.

6.2.3 River channel management challenges

A challenge for river channel managers is to determine the impact of adjustment and disrepair of the mill sites on the geomorphological stability of the river-channel. Such a challenge is not confined to the Tillingbourne but many similar scale river channels in England and Wales. For example, the author presents a study investigating three mill sites on the River Loddon, Berkshire (NRA, 1995a). Removal of, or modification to, these structures may potentially provoke a destabilising morphological reaction as the channel seeks to establish a new equilibrium condition with changing gradient and stream power. The continuum of sediment transport through any one given reach will exert an influence upon adjacent reaches, therefore, the removal or modification of weirs at any one site cannot be viewed in isolation from adjacent reaches. The failure of an existing structure, through natural deterioration, may potentially have rapid and widespread implications for channel adjustment. This may include the incision of the upstream bed which has accreted behind the former impounding structure with the consequence of increasing the sediment load carried downstream which itself may lead to exacerbated siltation rates in the lower reaches. Channel adjustment will attenuate progressively as new equilibrium gradients are sought.

It may be argued that a return to such naturalised conditions should be advocated promoting a river's effective self-regulation. However, consideration must be given to:

a) Human development extends beyond the boundary of the river channel itself to the riparian zone and to the floodplain. Many of these changes were brought about in parallel with the developments of the mill, communications and floodplain land-use. Any return to naturalised conditions of the river channel must also carefully consider the implications for associated change to the wider river corridor environment.

b) Despite representing an artificial modification of the natural system, the mills, mill ponds and associated structures may have considerable heritage value worthy of preservation.

6.3 A METHOD FOR EXTRAPOLATING RIVER CHANNEL CHANGE INFORMATION FROM HISTORICAL GROUND-BASED PHOTOGRAPHS

6.3.1 Rationale and historical ground-based photographs

River channel changes on the River Tillingbourne (and similar low-energy rivers) are not readily detected from the conventional historical planform record due to the limiting resolution of these information sources as illustrated in Chapter 4. Cross-sectional information will extend the ability to represent the channel topographic form but, in the case of the River Tillingbourne, comprehensive cross-sectional records were not available. Furthermore, these conventional historical sources of information are limited in time as to how far into the past river channel changes may be reliably extrapolated. Typically, maps pre-dating the Tithe Communication Survey sheets of the mid 19^{th} Century have been omitted from historical analysis on the basis of poor resolution and perceived planimetric inaccuracy (e.g. Hooke and Perry, 1976). This has tended to limit studies of river channel planform change in the UK to approximately the last 150 years. While this time scale may be deemed appropriate for relatively dynamic river channels such as the River Towy (see Chapter 4) which have demonstrated that contemporary adjustments may be attributed to stimuli over this time scale (e.g. in the case of the River Towy to railway construction and gravel extraction), for rivers such as the Tillingbourne, the history and nature of river channel adjustments may be in response to human-induced stimuli that may preceed these information sources.

In this respect, the geomorphologist concerned with extrapolating patterns of river channel change must seek alternative sources of historical information with which to reconstruct the river channel change:

a) Historical information within the period of the conventional historical sources of information which can provide an alternative means of assessing change in the last 150 years (e.g. Ordnance Survey sheets).

b) Historical information which may extend the period of observation beyond the scope of conventional sources of information (greater than 150 years).

In both cases, the geomorphologist may have to accept a loss of information accuracy components of inherent error (e.g. through generalisation) and the ability of the investigator to extrapolate river channel change information from these information sources in an appropriate manner.

Historical ground-based photographs provide one such solution and directly address the first issue because photographic records are available, but will not predate the last 150 years. However, many of the ways in which historical ground-based photographs may be collected, handled and interpreted are similar to those applied to historical drawings, etchings and written records. The same methodology may be appropriate for these sources of information extending the period of observation beyond 150 years.

Historical ground-based photographs may be recorded for a number of reasons and may not necessarily be taken for the purpose of recording river channel character. For example, photographs may be taken to record the image of features adjacent to the river channel such as buildings, bridges, gardens etc. The fact that the river may be recorded in this image may have been of incidental concern to the photographer. The ability of the photographic image to yield information of use to the investigation is therefore highly variable. Furthermore, images may be individual (e.g. a single photograph representing one section of the river channel at one moment in time) or part of a sequence of photographs representing different reaches of the river channel.

Taken at ground level the photographs may not necessarily suffer problems of overhanging vegetation as may be experienced by aerial photographs, although vegetation may still obscure the view to areas of the image.

6.3.2 Historical information for the River Tillingbourne

Historical reconstruction to illustrate development in the Tillingbourne Valley and the response of the River Tillingboune is reliant on the ability of the historical evidence to reconstruct past channel conditions. A variety of secondary sources of information, including cartographic evidence and historical ground-based photographs were used in conjunction in the analysis (Table 6.1). Even though the planform information is of insufficient resolution to render the evaluation of planform indices of river channel change, the cartographic evidence proved helpful in determining catchment-wide changes such as changes in riparian land-use, and in determining land drainage (for example, from disused watercress beds) and discriminated extensive siltation of the larger mill ponds. Information extending beyond the last 150 years relies upon written accounts and artistic impressions readily available from the Surrey Public Record Office (At Guildford and Kingston upon Thames) and through local investigation such as local interest groups (e.g. the Surrey Industrial History Group) and through informal interviews with land owners (e.g. the Estate managers).

A set of black and white historical photographs was available for the entire watercourse from the River Wey confluence to Abinger Hammer (representing the majority of main channel). The photographs were taken in 1935 for the specific intention of characterising the river channel. As such, each photograph is accurately located on a basemap and is supported by a short written statement noting the channel condition.

Date	Source of Evidence	Extent	Type
1896	1st Edition OS, 1:2500	Main channel complete	Graphical
1934	Provisional Series OS, 1:2500	Main channel complete	Graphical
1935	Oblique photographs	River Wey - Abinger Hammer	Graphical
1997	Oblique photographs	River Wey - Abinger Hammer	Graphical
1997	Geomorphological survey	Main channel complete	Graphical / Statistical
1998	Geomorphological survey	Main channel complete	Graphical / Statistical
1998	OS Baseplan, 1:2500	Main channel complete	Graphical

Table 6.1 Historical sources of information used in the River Wey investigation

6.3.3 Information collection

15 of the 1935 historical photographs were obtained from the Environment Agency as acting curators of the photographs. The photographs and accompanying notes were obtained in original form as prints and hand written paper sheets respectively (original negatives were not available).

In order to provide a comparison to these 1935 a detailed contemporary geomorphological survey was undertaken from the River Wey confluence to Abinger Hammer. A key component in this survey was to relocate and re-photograph each of the 15 images. The contemporary survey was undertaken in the same season (March/April) as the 1935 photographic survey in order to minimise discrepancies arising from mis-perceptions of channel condition due to seasonal channel differences such as within-channel vegetation. Because the locations of the historical photographs are spatially fixed, the re-survey comparisons are limited to the sites identified from the original survey.

Accompanying the 1935 photographs is a 1:50000 scale map depicting the location of each photograph with relation to the watercourse (Figure 6.4). This map scale was inappropriate for field use as deemed too generalised. The information regarding the photograph locations is transcribed onto contemporary 1:2500 scale Ordnance Survey sheets. Transcription of the photograph locations is variable based on the ability to place points relative to planform characteristics, bridge junctions, fence-lines and buildings. A lack of large scale development within the catchment meant that in many cases these features were represented largely unchanged over 65 years. Relocation in the field involved walking to the approximate point indicated

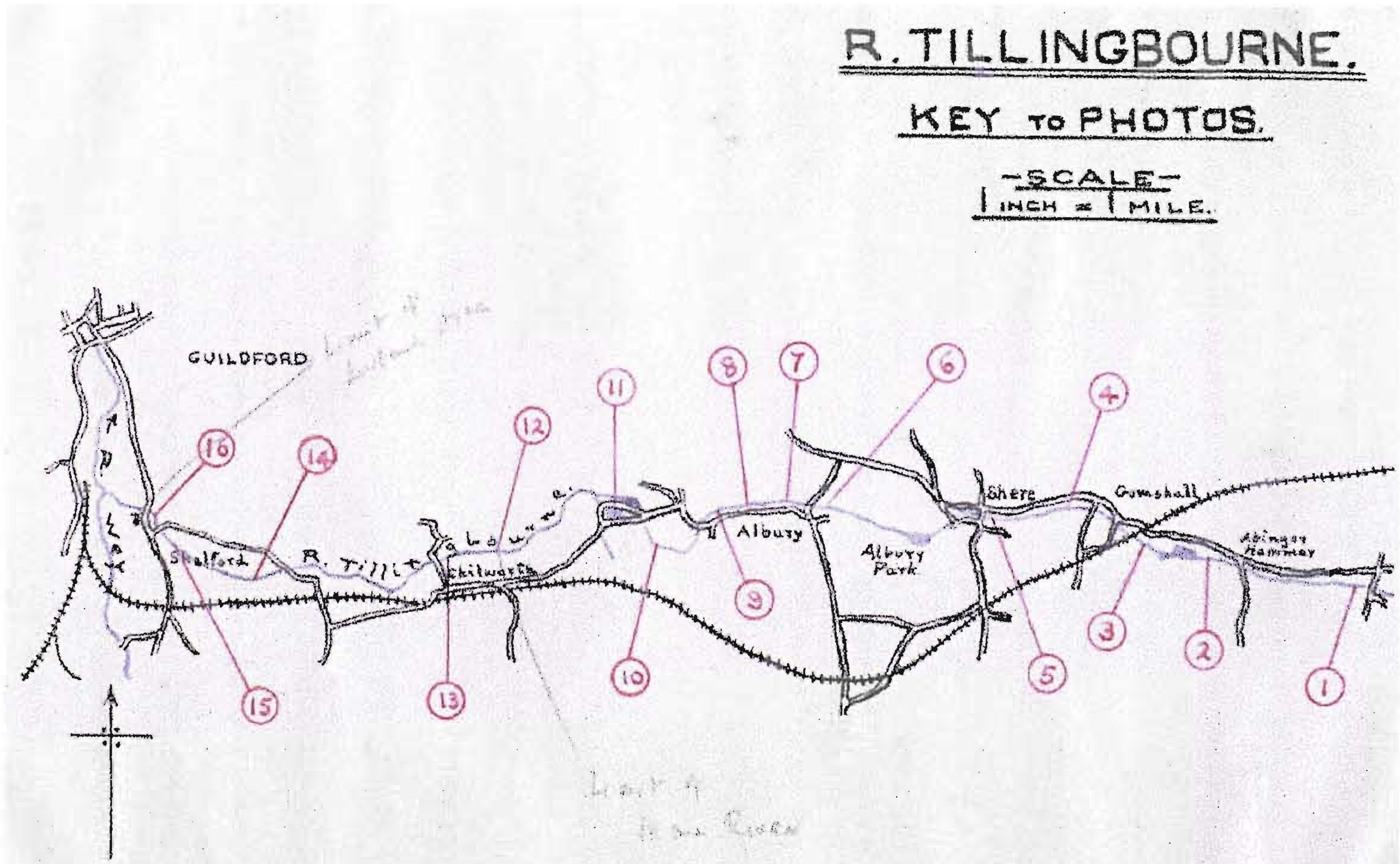


Figure 6.4 Map accompanying 1935 historical ground-based photographs of the River Tillingbourne

on the 1:2500 scale map and, with a high resolution copy of the 1935 photograph for reference, attempting precisely to relocate the photographers location and bearing in 1935. Furthermore, the historical photograph can be used in-situ to direct the field investigator to features of geomorphological interest in order to conduct a more detailed field survey. Geomorphological field survey techniques followed contemporary guidelines defined by the Environment Agency to record a variety of channel features at each site.

6.3.4 Information handling

Because of the semi-quantitative nature of the study, information handling is limited to simply printing the contemporary photographs and orientating their position relative to the accompanying basemap.

6.3.5 Information analysis

The interpretation of river-channel change at each of the 15 sites is based upon the comparison of information in the periods <1935, 1935, 1935-1998. Channel condition prior to 1935 is based upon the interpretation of supporting historical evidence to construct a qualitative impression of change. The comparison between the historical ground-based images is based on a qualitative estimate of change rather than attempting precisely to infer measurements of channel form (see Figure 6.5). For example, the photographs were able to yield information regarding within-channel changes such as berm development, bank slumping, and presence/absence of channelisation. Vegetation change also provides a helpful means of indicating changes in riparian land use and channel stability. In this way, the comparison

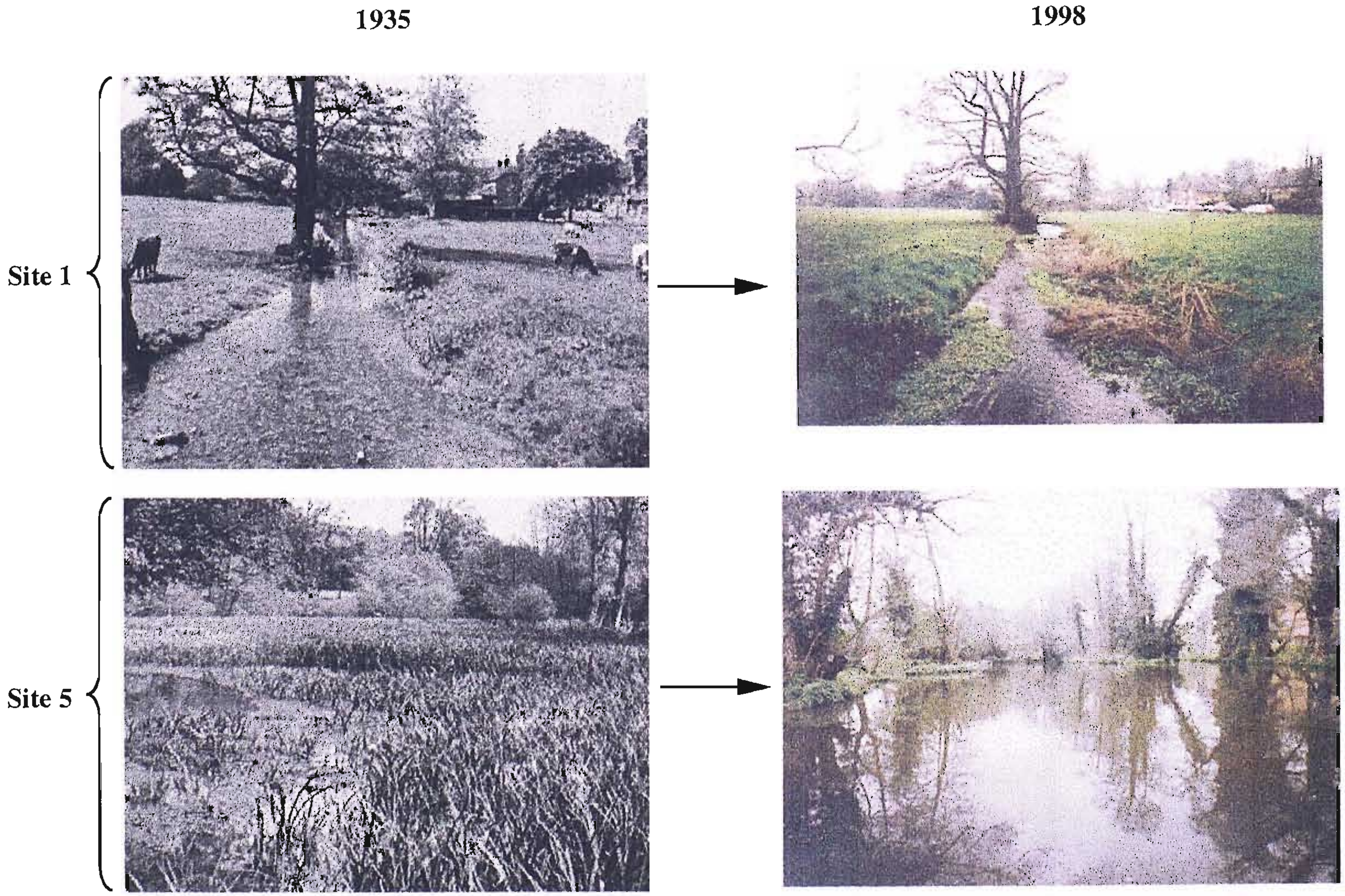


Figure 6.5 Examples of comparative photographs (1935 and 1998) for two sites on the River Tillingbourne

between the images allowed the 'direction' of channel change to be inferred and the 'relative' magnitude and direction of change may be estimated for the following conditions:

a) Channel Modification - considers the history of direct human modification, pre and post 1935.

b) Channel Recovery - an estimate of the channel reaction to conditions prior to 1935 and mid-20th century change (1935-1998).

c) Channel Stability - Determined on the basis of long-term (1935-1998) change and contemporary observation.

The assumption is made that the magnitude and direction of the change is progressive between the representations. Certainly, there is insufficient temporal resolution to provide estimates of anything more than the net change between the two images.

6.4 ASSESSMENT OF ERRORS ASSOCIATED WITH THE METHOD

6.4.1 Introduction

By the very nature of the qualitative enquiry, the assessment of errors associated with the methodology prompts a qualitative estimate of Total Error. Quantitative assessment is inappropriate because it assumes that numerical values may be attributed to the components of inherent and operational errors. However, it would be wrong to assume that simply because a qualitative means of comparison is taken that errors will have any lesser significance. Information mis-representation and mis-interpretation is as important in this example as with planform and cross-sectional information. This section therefore investigates the nature of the component inherent and operational errors and attempts to determine their significance.

6.4.2 Inherent errors

These are errors that are associated with the individual photographs and their location and orientation with respect to the river channel. Each component may be considered independently.

Errors associated with the photographic image

The 'accuracy' of the photographic image is based on physical characteristics of the image and geomorphological questions that the investigator asks of the photograph. For example, a question seeking simply to establish the morphometric relationship between bed, bank and vegetation will be much less demanding than questions which require the extraction of quantitative indices of river channel change features. Lane *et al.,* (1994), for example, demonstrate the use of oblique ground-based photography to obtain photogrammetric pairs of images to estimate the extent of river bank erosion on a pro-glacial stream from the Arolla glacier, Switzerland. In this case, the parameters governing the acceptable tolerance of spatial accuracy are pre-determined and the image must be required to fulfil these requirements.

However, in the case of retrospective studies which must make use of available photographic evidence, the ability of the image to represent river channel features is a function of:

a) The spatial resolution of the image. This is determined by the relationship between the lens parameters, the distance between the feature of interest and the recording medium (e.g. film or pixel array). Light conditions will also determine the brightness and contrast of the image. In theory, features may be resolved by the individual grains of photographic film or individual pixels of the array. In practice however there may be insufficient contrast visually to define features between adjacent photographic grains or pixels. This ability is also a function of whether the image is recorded in colour or black and white which will further influence the ability of the investigator to resolve and identify river channel feature characteristics.

Computer-based image processing software may go some way to improving the situation by digitally manipulating the image representing the river channel. For example, areas of the image may be enhanced (e.g. 'contrast stretching') to highlight features which may not necessarily be immediately clear to the naked eye.

The spatial resolution of the photographic image may also diminish with time. For example, the prints of the River Tillingbourne were reasonably well preserved, but similar examples discovered for other river channels showed obvious signs of fading and loss of feature definition.

b) The temporal resolution of the photographic image may not always be known. In the case of the River Tillingbourne photographs the accompanying information indicates the date the photograph was taken to the nearest month. However, similar images discovered may be undated. The archive itself may be able to provide an indication of the date of the photograph (...."Everything in that box is from the 1930's") but usually dating must rely on corroborating evidence, either between features represented in the image or from the nature of the photograph itself (e.g. the paper used, the method of printing).

The location of the image in the watercourse

Historical photographic records may not necessarily be located accurately in space. In certain cases the information contained within the photographic image itself may be sufficient to allow a precise estimate of location and direction (bearing) of the photograph be estimated (e.g. bridges and buildings). The continued presence of such features may be helpful in locating these photographs for contemporary re-survey.

In the case of the River Tillingbourne study the location of the 15 photographs are mapped at approximately 1:50000 scale. At this level of planimetric representation identifying the location within the watercourse was variable dependant on position with regard to their proximity readily identifiable features. However, it is accepted also that the original photographer may have mis-represented the location of the photograph on the original accompanying 1:50000 scale map.

The photographs do not represent an individual point or cross-section in space, but observe a reach of the river channel with diminishing resolution as features lie progressively further from the camera from foreground to background. The resolution in space between photographs may also be highly variable. In certain instances the images may only allow estimates of river channel change to be extrapolated for individual sites. In the case of the River Tillingbourne photographs were separated by up to 500 metres. At this level of spatial resolution it would be inappropriate to assume that each photograph is representative of a continuous geomorphologically homogeneous reach, rather in this case the development of each reach associated with the photograph is considered independently and qualitative estimates are drawn regarding the association between adjacent photographs based on corroborating evidence.

6.4.3 Operational errors

Operational errors are considered to include those of relocation of the original photograph locations in the field (and their bearing) and errors arising from the comparison between the images in space and time.

Field relocation

The ability to relocate the photograph with confidence varied dependant on the nature of the photograph and the condition of the river channel. For example, in certain images, the presence of fixed objects in the image (e.g. buildings) allowed precise relocation estimated to within a few metres of the original. In other cases, particularly where the river channel and floodplain has undergone marked change there is less certainly and greater reliance on the cartographic evidence. In such cases, the relocation may be said to be a 'best estimate' given the available information and the image provide may not necessarily provide an exact match to the 1935 photographic image, but none-the-less is assumed to be representative for the reach. Such an approach is considered valid to this analysis because the photographs do not represent an individual point in space.

Image comparisons

The ability of the investigator to compare the images is dependent on the representation of the river channel in both images (as noted in the previous section). Operational error arising from comparison is therefore a function of perceptual ability which will vary between images and through the ability of the investigator to interpret change in the basis of the available information. In this respect, because the analysis is qualitative and therefore somewhat more subjective in nature the experience and the ability of the investigator mentally to associate the images to his/her experience is important. Success criteria for such subjective assessments are difficult to assess.

Instead a surrogate value was sought. A simple test was conducted with the contemporary river channel photographs and the geomorphological field survey notes obtained in 1998. Semi-quantitative estimates of river channel characteristics were extracted from the photographic images independently of the field notes and then later compared. In most cases the ability to extrapolate general morphological characteristics, such as an estimate of the channel bankfull or low flow width, bank angle etc, closely matched the measured field estimates. This ability decreased for river channel features in the image background and with increasingly dense vegetation cover.

6.4.4 Propagation of error

Errors are propagated through each stage of the historical investigation from information collection, handling and interpretation of the results of the analysis. Given that the methodology infers the direction of change and does not attempt to quantify indices of channel form or river channel change then the estimate of Total Error is somewhat more subjective than might be applied to quantitative methodologies.

In the case of the River Tillingbourne surrogate vales may be used to aid this assessment, for example, while it is not always possible precisely to relocate the position of the photographer in the field (estimates assumed a value to within 50m in this case based on available evidence) the photograph is said to be 'representative' for a given reach . In certain cases, if sufficient doubt existed between photograph and location the particular photograph may be omitted from the enquiry. Corroboration using spatial association between the changes observed from the photographic evidence by comparison to estimates extrapolated from contemporary geomorphological survey provide the investigator with a useful means of evaluating the evidence presented in the photographs. As such the propagation of error is illustrated in Figure 6.6 which provides a comparison for any two chosen photographs representative for one site location. The potential for error increases as a function of the inherent photographic information (image error and positional

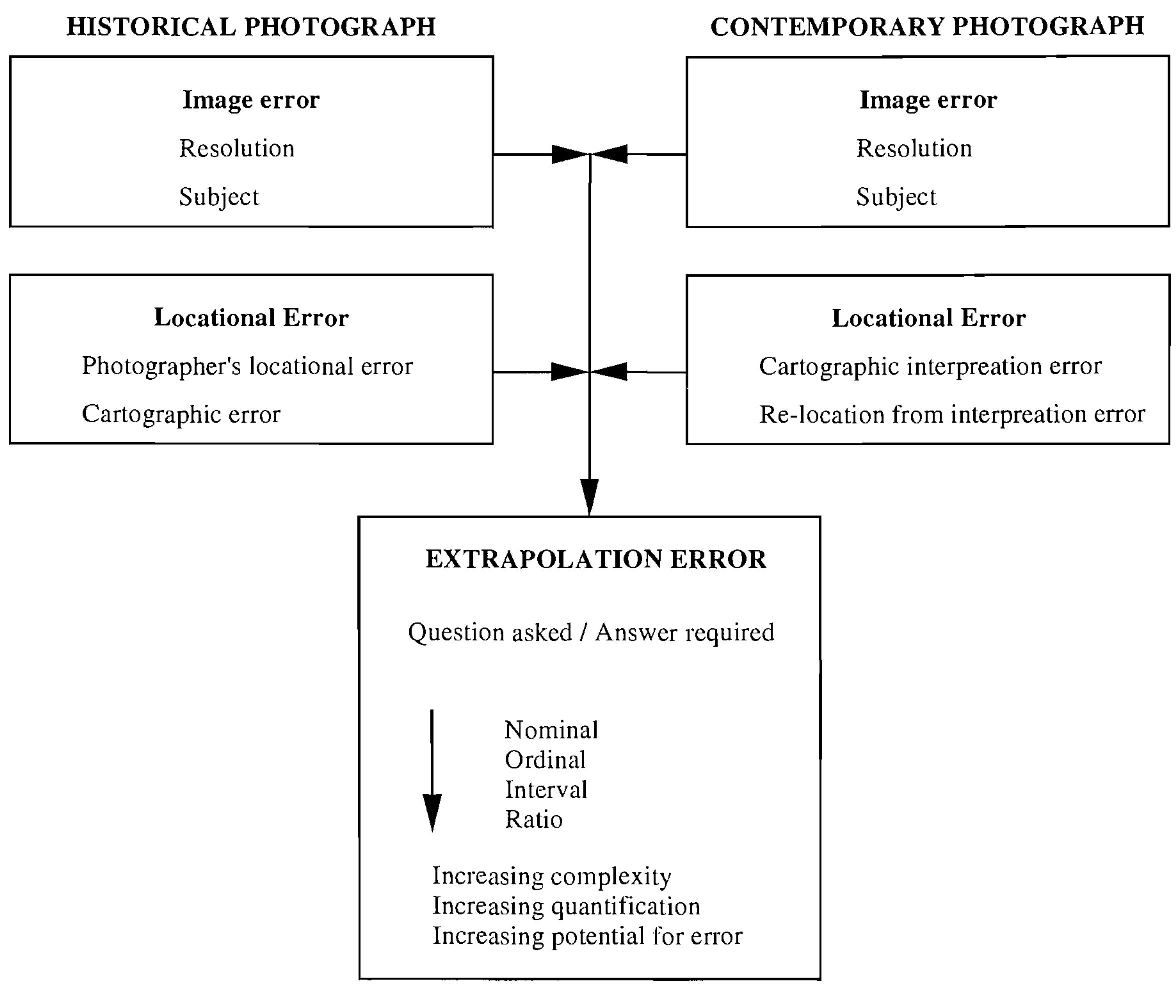


Figure 6.6 The transcription of errors in the comparison of ground-based historical photographs

error) and the channel change questions asked. Greater potential error is associated with increasing complexity required in the answer to these questions.

6.5 RIVER CHANNEL CHANGES ON THE RIVER TILLINGBOURNE

Table 6.2 provides a summary of results of the historical enquiry for the River Tillingbourne. Estimates of river channel stability are illustrated graphically in Figure 6.7.

The historical legacy of channel modifications, particularly channel adjustment resulting from milling has effectively divided the river channel into a number of distinct sedimentary zones each characterised by a sediment sink at the downstream limit. Sediment transport through the watercourse is believed to be punctuated and largely dependent on localised sediment type. Owing to the former density of mills the combined effect of reduced peak flows with backwater conditions favours net channel sedimentation. Evidence of channel erosion tends to be highly localised and moderate, promoted by the cohesive and typically armoured nature of the channel substrate.

The pre 1935 channel was one that was dominated by the mills and the historical evidence suggesting that reaches between mills were carefully maintained to ensure their efficiency. Fisheries and water-cress farming were important industries, but evidence suggests that their historical influence on channel morphology were relatively insignificant. The 20th century has seen the dereliction of the majority of the mills on the Tillingbourne, however, the overwhelming impression is that the

Site	Modification	Recovery	Stabilty 1935 - 1998	Notes
1: Abinger Hammer cricket ground (TQ 096474)	Straightened and widened <1935 Cricket ground post 1935	No change 1935 Minor within channel sedimentation 1998	High stability (no change) Moderate insensitivity to channel modification	Paddingston Mill formerly u/s, low sediment throughput. 'Managed' riparian zone, no overhanging vegetation.
2: u/s ford at Abinger Hammer (TQ 092474)	Straightened channel <1935. Abinger forge mill originally u/s	Berm development by 1935, minimal change to 1998	Moderate stability (no change)	Abinger Hammer Mill formerly operational u/s. Marshy backwater <1935, drained and straightened: Progressive recovery, quasi-stable conditions.
3: Wonham way (TQ 088476)	Former watercress beds adjacent channel. No direct modification to channel	Minimal change 1935 -1998. Tree-lined channel 1998.	High stability (increasing stability)	Trend towards increasing stability with near complete recovery of riparian conditions.
4: Netley Mill Pond (TQ 079479)	13th century Mill Pond, mill operational until 1907. Mill pond restoration 1970, periodic (10 year) dredging.	Pond siltation. High siltation (recovery) by 1935. Complete siltation by 1970. Restoration of modification condition 1998.	Unstable 1935 (siltation), tending towards stability (1970). Unstable 1998 (siltation) requiring periodic dredging)	Excavation of the mill pond 1970 - removal of 27,000 Tonnes of silt (>63 years of deposition). Restoration of mill pond maintains unstable condition. Historically the first major sediment sink d/s of Paddington Mill.
5: Shere Lower Mill Pond (TQ 076479)	Mill pond (<1086). Mill non operational 20th century. Mill pond restoration 1993.	Pond siltation. High siltation (recovery) by 1935. Minimal recovery in 1998 to restored mill pond condition in 1993.	Unstable 1935 (siltation) tending towards stability (1993). Unstable 1998 (siltation) requiring periodic maintenance (weed removal)	Re-excavation of the mill pond in 1993, maintains unstable condition, although rate of sedimentation reduced with major sediment sink u/s with the restoration of Netley Mill Pond.
6: Albury Park (TQ 060479)	Ornamental based modification from 17th century - former chain of ponds. Channel straightened and widened and toe-boarded <1935. Toe-boards removed <1998, channel allowed to return to a naturalised condition. Low weirs and bankside management evident.	1935: Channel conditions maintained by toe-boards, minimal recovery to imposed conditions. 1998: Widescale recovery, reduction of channel width, sinuosity increasing.	Moderate stability. 'rapid' recovery from <1935 condition, quasi-stable conditions persist	Removal of toe-boards has allowed accelerated recovery of the channel towards naturalised condition. Recovery continues, although restricted by routine channel maintenance.

Table 6.2 River channel changes on the River Tillingbourne (see also Figure 6.2)

7: Albury Estate (d/s from pumping station) (TQ 058479)	Indirect channel modification though control of riparian zone - grazing. Low weir (mid 20th century)	Minimal change 1935, channel conditions maintained. Grazing restriction - recovery of riparian zone vegetation (tree-lined channel by 1998). Moderate channel change >1935 to present.	High stability 1935. Moderate stability 1998 with a change to more naturalised riparian conditions.	Grazing access limited bankside vegetation development. Increase in channel debris and resulting instability evidenced (e.g. tree bowls curving through bank slump). Low weir locally reduces excessive change.
8: Albury fish ponds (W.limit) (TQ 054479)	No modification recorded - naturalised wooded channel	No perceived change in channel condition <1935 - 1998.	High stability (no change)	Albury estate land, unmodified ancient deciduous woodland. Highly naturalised stable channel.
9. A248 bridge (TQ 047476)	Originally a mill pond <1896, Pumping station <1935. Artificial bypass channels constructed around weir.	Minimal change 1935 - 1998, Minimal sedimentation.	High stability 1935 (no change)	Although the mill has fallen into disrepair, the site still maintained by the Albury Estate. Evidence for bankside tree removal and upkeep of pump house.
10: Postford Pond (TQ 040479)	Posford Lower Mill pond <1693. Non-operational as a mill in 20th century. Channel modifications. 1992 - modifications to raise bed levels to direct greater flow to S.Channel at Chilworth. 1996/7 - houses and estate offices at old mill site and channelisation immediately d/s from Pond.	<1935 - Map evidence for siltation. 1935, continued (and noted) siltation of pond and marsh formation. 1998, siltation continues at pond margins, but stage maintained through d/s channel works.	Low stability 1935 (sedimentation). Moderate stability 1998.	Remains an extensive ponded area, remains a large sediment sink, although rate of change slow by virtue of pond extent and recent modification d/s.
11: Chilworth gunpowder works (n. branch) (TQ 031476)	Natural branch of Tillingboune - part of extensive modifications throughout reach at the gunpowder works <16th century - early 20th century. Flow divided to south (artificial) channel.	Progressive recovery and naturalisation through 20th century. Sedimentation of south channel maintains dominant flows to north channel. 1935, naturalised high sensitivity channel, evidence of change (enlargement and deposition) - restoration of naturalised form.	<1935, high stability - channel (managed). 1935, unstable - increased flows, naturalisation. 1998, moderate stability (quasi-equilibrium), aided by reworking of north channel 1991/2.	Complex interaction of flows <1935 divided by numerous channels connecting north and south channels. Siltation in artificial channels from mill closure re-directs flow to south channel promoting adjustment. Stability improved with dredging of north channel 1991/2.

Table 6.2 (Continued) River channel changes on the River Tillingbourne (see also Figure 6.2)

12: Chilworth gunpowder works (W.limit) (TQ 025475)	Confluence of north and south channels, small pond <16 century, feeding Mill d/s, Blacksmiths Lane. Mill provided water power to pump water to St.Martha's hill reservoir early 20th century. Mill disrepair by 1935, maintenance of pond for fisheries. Periodic draining, desilting to present - remains a fishing pond.	Prone to siltation but constant management limited siltation through periodic dredging (to date). 1935	1935, high stability (no change).	Closure of the mill at blacksmith lane and the water pump, but weirs remain if in disrepair. Modifications to north and south channels u/s have maintained balance of sediment input from early 20th century - present.
13: East Shalford (u/s Manor House Bridge) (TQ 013474)	No modifications recorded at this site. No discernible backwater influence.	Channel remains sinuous. Gravel bed high sensitivity channel	High stability (no change). Minimal discernible difference 1935 - 1998	Indirect effect of sediment starvation from u/s from former mill at Blacksmith lane. Weirs remain. Natural, geomorphologically diverse channel.
14: u/s Shalford Mill (TQ 003475)	Backwater channel to Shalford mill <1086. Ornamental gardens mid 18th century, water backed up behind weir immediately d/s through gardens. Mill derelict 1935. Restored by 1998 - Contemporary maintenance of weir.	Sedimentation evidenced by dramatic reduction of mill pond immediately d/s 1896 - 1934 to marsh. 1935-1998 remains semi-naturalised channel.	<1935, unstable, sedimentation of mill pond. 1998, moderate stability, quasi-equilibrium condition.	Site maintained with dis-use of Shalford mill despite loss of mill pond. Stage maintained in backwater to gardens by weir, continued, but much reduced levels of siltation into 20th century.
15: d/s Shalford Bridge (SU 999479)	Maintained channel d/s to confluence with River Wey. u/s Shalford mill <1086.	Sediment supply increased with mill disrepair early 20th Century, low gradient to River Wey enhanced deposition. Minimal change late 20th century, low rate of sedimentation.	<1935, low stability. 1998, moderate stability.	Restoration of Shalford mill has arrested quantity of sediment throughput.

Table 6.2 (Continued) River channel changes on the River Tillingbourne (see also Figure 6.2)

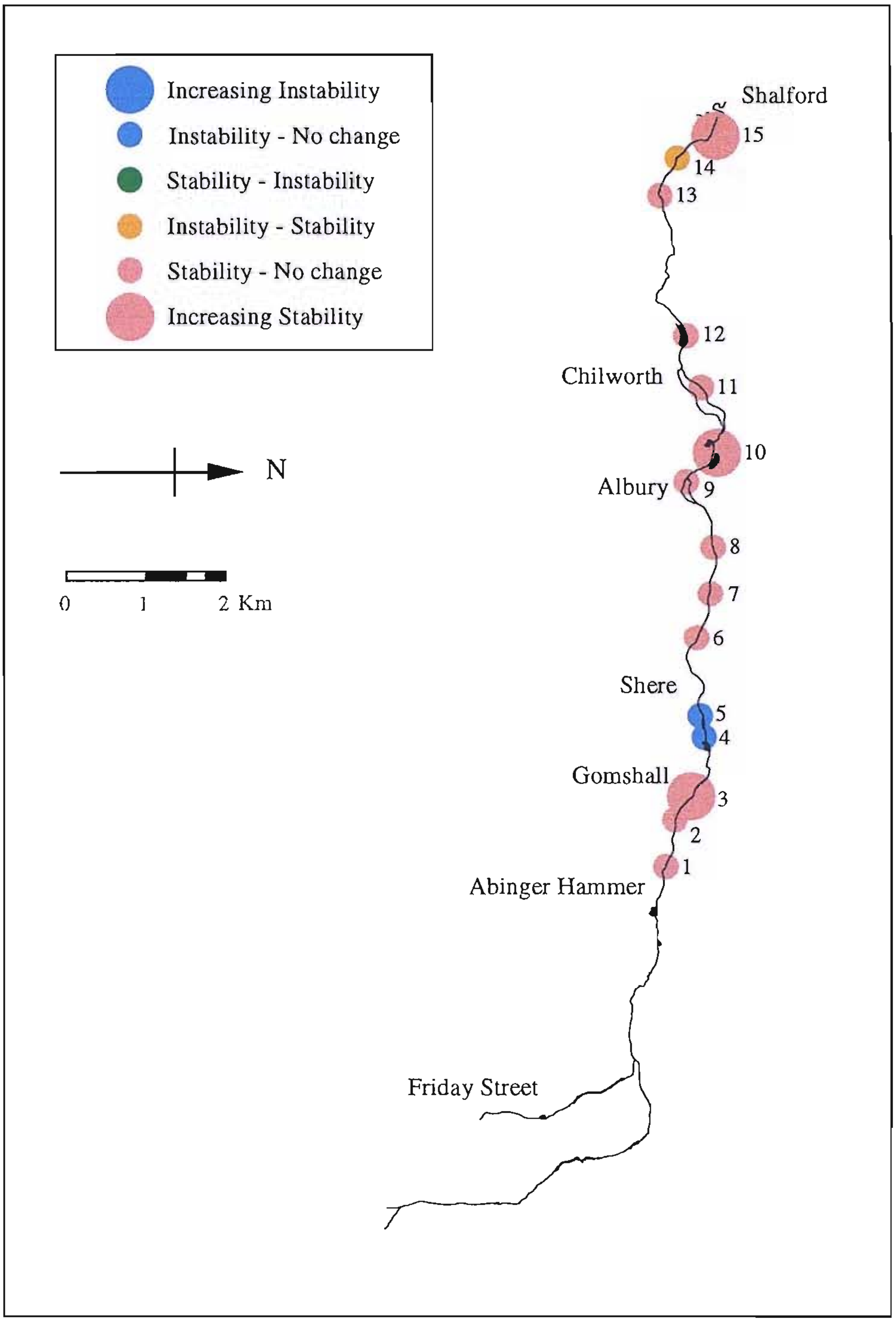


Figure 6.7 River Tillingbourne contemporary channel stability

channel 'infrastructure' remains and the macro-geomorphological form of the watercourse is still determined by the weirs and sluices serving the former mills. The evidence suggests that overall the watercourse has greater geomorphological stability now than was the case in 1935. This is believed to result from an increased trend towards the preservation, restoration and renovation of the existing mills and associated structures toward the latter part of the 20th century. This has arisen through the action of individual riparian owners (e.g., Netley Mill), through maintenance by the estates, through imperative (e.g. flood protection at Chilworth Gunpowder Works) and/or where the mill has been converted (e.g. housing at Posford Mill). In all cases, stability has been achieved through maintaining the channel within a quasi-equilibrium condition achieved through continuous periodic maintenance, a contradiction considering that, whilst largely 'naturalised' the channel macro-form of the river Tillingbourne is not 'natural'. This trend is likely to continue, particularly as many of the mill ponds are now actively managed as game fisheries and the angling lobby, in close association with the estates, have sought to carefully preserve the character of the watercourse. For the immediate future at least the continued stability of the river is assured.

6.6 CONCLUSIONS

The River Tillingbourne represents a river channel that has been perceived as one that is both natural and one that remains in a state of overall geomorphological quasi-equilibrium. This perception arises because the river channel is situated within a rural setting, has (for the most part) a natural bed and banks and exhibits no obvious evidence of instability. However, sediment transfer within the channel is artificially modified by long-term human activities and the supposed contemporary stability is dependent upon periodic river channel maintenance.

The geomorphological problem associates well with the type of historical investigation (demonstrated in this chapter) because the oblique historical photographs (used in conjunction with contemporary observations) are of sufficient spatial resolution to allow qualitative comparisons of channel form. Additionally, the photographs span a 64 year period that was discovered sufficient to identify gross river-channel changes. 'Traditional' historical sources of information (e.g. planform and/or cross-section records) were not available at sufficient spatial resolution with which to resolve the changes identified through comparison of the historical oblique photographic record.

The historical evaluation is qualitative. Qualitative information should not be considered any lesser value than quantitative information, simply that the information is different. This qualitative interpretation of the oblique photographs has yielded important information with regard to river channel 'patterns' of behaviour and highlights and prioritises reaches requiring management attention if contemporary patterns of river channel form are to be maintained.

The River Tillingbourne is not unique in the Thames catchment in terms of its history of modification and many other rivers share similar modifications over similar time scales. Unlike many of its urban counterparts land-use change in the Tillingbourne valley has been subtle rather than the stark contrast of extensive late 19^{th} to 20^{th} century channelisation that has tended to obscure many of the earlier modifications of rivers in, for example, the London Basin. None-the-less, it can be demonstrated that the contemporary geomorphological stability of the river channel is inextricably linked to its history of modification. Perhaps a perception of persistent stability and limited adjustment has lead academic research to focus more on larger more active channels for which the historical source information (typically planform in nature) reliably to resolve quantitative indices of change. In addition, understanding past human activity may be used to provide analogies for the future. This is not to assume that given the same type of human action on a similar river channel that the same response will be recorded (indeed, different reaches on the River Tillingbourne itself show different morphological reactions to similar human-induced stimuli), rather, this information may be used to construct a portfolio of likely reactions that may occur and to help refine the managers decision making process.

6.7 SUMMARY

River channel changes occur at spatial scales that are not readily detected by more traditional sources of historical information. These river channels may be considered stable by comparison to upland or piedmont zone river channels in England and Wales because stability has typically referred to absolute measures of river channel change (e.g. absolute measures of planform adjustment). However, contemporary observation and management concern has demonstrated that these rivers may exhibit patterns of instability that are associated with direct human river channel interactions over extended time scales. Instability is a consequence of sedimentary imbalances occurring at small (possibly sub-metre) scales.

The periods over which human interaction acts to affect river channel development may far outstrip the ability of traditional sources of historical information to discriminate river channel changes. 'Alternative' sources of information provide a means of supporting contemporary observations of geomorphological stability to place contemporary changes in historical perspective through aiding the interpretation of the parameters of changing patterns of river channel adjustment.

In many cases, the extrapolation of quantitative indices of change may not be possible with these alternatives. Qualitative assessments of river channel change are of no lesser importance. Where they may be demonstrated (as in the example provided for the River Tillingbourne) to provide a valuable contribution to understanding the morphology of the river channel they may then provide a valuable facet as an aid to the decision making process.

CHAPTER 7

APPLICATION TO APPLIED GEOMORPHOLOGICAL RESEARCH: THE RIVER WEY, HAMPSHIRE AND SURREY

7.1 INTRODUCTION

Previous chapters have illustrated how different formats of historical sources of information may be used effectively to extrapolate river channel change information. River channel change questions will define the level of accuracy demanded of the historical information and as such determine the requirement of the historical information. Chapters 4, 5 and 6 provide example methodologies in the use of a range of historical information sources to provide such answers and for each example examine the level total error as a means of understanding the confidence in these answers.

This aim of this chapter is to illustrate how historical sources of information may be used effectively to develop geomorphologically sensitive strategies aimed at addressing specific river channel management questions. The chapter addresses the example of the River Wey. The River Wey was extensively studied in early 1996 on behalf of the Environment Agency (1996a) in order to address a specific river channel management challenge. Sedimentation problems associated with direct human intervention with the watercourse have long been recognised, their alleviation requiring dredging ('sand panning') in order to maintain the navigable potential. The Environment Agency's terms of reference were to establish the contemporary river channel stability and geomorphological sensitivity to adjustment for the entire watercourse in order to provide a series of geomorphologically sensitive recommendations for appropriate mitigation of sedimentation problems.

This chapter will demonstrate how historical sources of information provided an invaluable asset to this enquiry. Firstly, in reconstructing river channel history through human activities and their potential impacts on channel morphology, and secondly, for providing more detailed site-specific information regarding historical river channel change. Furthermore, the chapter describes how the development of a GIS-based geomorphological database proved a useful aid in the handling and analysis of diverse sources of historical and contemporary information to provide the investigation with an effective means of disseminating information and presenting geomorpholgical information to river channel managers.

The specific aims of this chapter are:

a) To review the challenges for applied geomorphological research to aid geomorphologically sensitive river channel management.

b) To provide a background to the River Wey and the specific challenges facing river channel managers.

c) To describe a range of historical and contemporary geomorphological approaches used to identify 'Potentially Destabilising Phenomena' (PDP) (Sear *et al.*, 1995) which have influenced the contemporary morphology of the River Wey

d) To establish links between the contemporary channel characteristics and the impact of PDP in determining the morphology of the River Wey.

e) To identify geomorphologically sensitive recommendations in the immediate and long-term to address identified river channel management challenges.

7.2 THE CHALLENGE FOR APPLIED GEOMORPHOLOGY

Before this chapter addresses the specific example of the River Wey it is perhaps helpful to take a step back and consider the wider issue of geomorphological acceptance in river-channel management in England and Wales. In particular, why at a time when British academic geomorphology is at the forefront of academic research is there only now becoming a more widespread acceptance of geomorphological input to river channel management? Three possible explanations are considered:

Geomorphology as a subject is highly fragmented

Gardiner (1996) considers the view that the nature of physical geography has changed dramatically in the last 40 years, arguing that there has been a high degree of fragmentation within the discipline, particularly in geomorphology, with an associated loss of identity. Potential fractionation of geomorphology brings both advantages and disadvantages.

There has been a closer integration with associated disciplines such as hydrology, engineering and mathematics. This brings the advantage that engineers may gain an increased insight into geomorphological understanding and versa but may have the disadvantage that engineers may lay claim to geomorphological expertise but without necessarily a full geomorphological background. As such, the application of geomorphological knowledge may be mis-placed and promote mis-understanding and mis-application to applied research. This may potentially promote a loss of respectability for geomorphological information (Sear, 1994). However, it would potentially be wrong, for example, to assume that engineers are ignorant of all concepts that may be considered geomorphological. Likewise, the perception that the contemporary engineer is insensitive to 'conservationist' values is largely misplaced and an inherent legacy of river engineering of the past.

Newson (1992) argues that a consequence of over-specialisation through increased fractionation, geomorphologists are in danger of loosing touch with broader holistic aspects of the subject. This is particularly important in the communication of geomorphological information concerning river channels to practitioners who may have little geomorphological knowledge. The geomorphologist must therefore strike a balance, without wishing to degrade the value of information must seek to communicate geomorphological information in terms that are readily understood.

Geomorphology has not traditionally been regarded as a professional subject

The perception of geomorphology as a science is different from other physical disciplines. Geomorphology is not an exact science and the application of geomorphological expertise to aiding what might be considered as much a social challenge as a physical challenge is even less determinate. For example, Casti and Karlqvist (1991) argue that scientific solutions attempt to predict the outcome of physical change in terms of a given set of determinate 'rules' which when generally accepted may become upgraded to 'laws'. As such, disciplines such as water engineering and hydraulics may model and predict outcomes that may be readily defined by a set of criteria. While reductionist standpoints in geomorphology may favour similar rationalisation, geomorphological experience has consistently demonstrated that readily quantifiable outcomes, particularly when applied, may not be so simple. Leopold and Langbein (1962), for example observe that physical laws may be satisfied by any number of different combinations of independent variables.

Schumm (1991) offers one potential explanation, here he talks of geology, but essentially the argument transcribes for geomorphology too,

"This is a peculiar attitude that seems to have been generated by the inability of the geologist to produce quantitative 'laws of nature'. Indeed the consideration of both vast spans of time and large areas is not common to other physical sciences .... The earth scientist deals with complex systems that function over long periods of time, and each system, although not unique, may be singular. That is, each system is different from similar systems, and each may reflect processes no longer active at a particular location (e.g. glaciation). hence the opportunity for reproducibility and falsification is minimal. Therefore, it is not surprising that geologic and geomorphic predictions may have 'low resolution' and may be weak in comparisons to other sciences." (p.4).

Consequently the geomorphologist may be considered prone to 'arm waving' (Downs and Thorne, 1996) for failing to provide quantifiable deterministic relationships concerning the operation and future prediction of rivers. Two schools of thought exist.

The first is one pertaining to 'randomness' or the indeterminate interaction of events in nature, "an accumulation of numerous deterministic events into a complex and indecipherable tangle." (Mann, 1970). By taking such a stance the geomorphologist can be regarded as being stochastic in that the impression of future river channel behaviour will deal with the 'likelihood of' future adjustment. This view is supported by Graf (1984) who observes,

"Fluvial processes are so complex that it is unlikely that precise predictions are possible in any case, but alternative approaches utilising a probalilistc geographic approach may provide enhanced predictive capabilities." (p.959).

One such probabilty approach is adopted by Downs (1994) to predict the probabilty of river channel response variables based on channel characteristics determined from ground-based geomorphological reconnaissance. The method involves multivariate regression analysis as individual channel change parameters are either added or ommitted to determine the predictive channel response (sensitivity to the variable). Such approaches go a long way to providing a more 'scientific' basis for describing what remains essentially indeterminate fluvial activity by attaching confidence to the predictive outcomes.

The second school of thought argues that geomorphological behaviour which may be interpreted as random or chaotic would be possible to unravel as deterministic science given the 'detail' of information, e.g. greater resolution (Scheidegger, 1967). Such an approach is potentially more in line with other physical sciences and holds greater favour where river channel studies have attempted to deal with fluvially isolated reaches of channel at the small (engineering) scale. Geomorphological extrapolation and interpretation at the basin scale invariably involves a loss of resolution by comparison and thus the ability to predict similar indices of change with similar confidence is diminished.

By reducing river related challenges to individual reaches over short time scales it is not surprising that in order to attempt to overcome 'unexplained' river channel responses many engineering schemes in the past have been over-engineered and grossly detrimental to the river environment. Unfortunately, a significant lack of 'geomorphologically managed' examples in England and Wales provides little in the way to date of significant geomorphological Post Project Appraisal. This has brought about a degree of reticence by the water manager to accept geomorphological suggestions. The river channel manager must therefore seek a compromise between traditionally tried and tested engineering solutions which can provide clearly defined Standards of Service and geomorphological solutions which are largely untested.

In many ways the challenge in the drive to wider acceptance is to ensure that geomorphological understanding may be communicated in a manner that may be interpreted by river channel managers who are unlikely to have a geomorphological training, without appreciable loss of 'information'. In this sense, the principles outlined in this thesis concerning the propagation of information and information error do not end with the geomorphologist providing the results to an investigation but in ensuring that these results are interpreted and acted upon in a meaningful manner. Communication is all important, for example, the geomorphological notion of to 'Do-Nothing' has typically been used in an applied sense to indicate that a degraded reach be left to attain a condition of natural dynamic equilibrium through self adjustment, or, the maintenance of near 'pristine' conditions of a high sensitivity reach through non-intervention. The term 'do-nothing' may imply a very different meaning to a practitioner with only limited geomorphological understanding. In this case NRA (1996) indicates that the term 'Allowed Natural Adjustment' be more appropriate,

"This policy involves on-going monitoring of the problem and periodic review of the management options and it does not equate to 'doing nothing' ." (NRA, 1996).

Similarly, Beschta and Platts (1986) note that terms such as channel 'improvement' and 'enhancement' may be interpreted by engineers to indicate action that promote steady-state stabilty (e.g., through channelisation). In the extreme, poor communication may have implications for professional negligence and liability (Jerram, 1991). To some extent potential problems may be overcome with increasing exposure of the non-specialist to geomorphological information. For example, the Environment Agency, Thames Region has produced a series of 'Geomorphological Guidance Notes' for internal use (Brookes, 1995).

Finally, Brookes (1995) notes, that unlike other water related disciplines there are, as yet, no professional geomorphological standards for applied geomorpholgical research and remarks that this contrasts significantly with other water related disciplines.

There is a traditional of engineering dominance in river channel management

The engineer's dominance over the river systems of the world prevails. River engineering can be traced back centuries to pre-industrial ages and heralded as some of the greatest achievements of humankind. In England and Wales river channel engineering can typically be found over extended reaches on the majority of rivers. The response of the river channel change is not always obvious. Brookes *et al.* (1983) note that between 1930 and 1980 some 8504 km of 35500 km designated main channel was channelised. Indirect influences of engineering work through flow and sediment regulation are more widespread and impossible readily to quantify.

However, such an engineering-based legacy of river engineering is fundamentally at odds with contemporary environmentally sensitive approaches to river management. Leeks *et al.* (1988) note that many rivers fall, "casualties of the hundred years of 'heroic' engineering guided by other goals, other public perceptions and not at all, it seems, by fluvial geomorphology" and consequently cost expenditure is concerned with "cleaning up after old sins".

This perceived 'failing' of engineering-based management to recognise the river channel as part of a system and the interactions of this physically based system with other systems (both physical and human) may stem from three possible issues highlighted by Newson (1992):

a) Land and water are a hydrological continuum and must be managed together.

b) Need to understand river phenomena in terms of the equilibrium condition of the site affected and, if possible, the system as a whole.

c) The nature and type of river management systems are critical to conservation.

Mitchell (1990) lends support to these arguments and states that for effective integrated management, in addition, the physical system interactions of the drainage basin must be considered in terms of their interaction with social and economic conditions that prevail for the basin.

The notion of success or failure depends on the criteria with which these schemes may be judged. Historically the incentive has been economic, driven by cost-benefit analysis. Were the same cost-benefit analysis performed from an environmental standpoint the outcomes may well be very different. The 1990's has seen environmental values permeate all levels of land-use planning and management in England and Wales and it is a statutory requirement of planners and river channel managers alike to fulfil and satisfy environmental criteria as set out by law (e.g. Gardner, 1988; HMSO, 1991). This has been significant in bringing about changes in perceptions and attitudes to environmental issues as a whole with inevitable consequences for the river environment. The question remains as yet unanswered as to the 'interpretation' of law and the statutory placement for applied geomorphology. In the meantime water managers have tended to adopt a half way house between traditional engineering values (e.g. see Charlton, 1982) and those of environmental restoration and enhancement and terms such as 'environmental engineering' and 'soft-engineering approaches' prevail.

7.3 A BACKGROUND TO THE RIVER WEY AND SEDIMENTATION PROBLEMS

7.3.1 Introduction

Geomorphological approaches have demonstrated their value in aiding river channel management decisions. For example, the author has undertaken several studies over the period of this PhD research which have demonstrated the value of geomorphological inputs to river channel management challenges (Table 7.1).

Of these, the River Wey example is summarised here. This example is chosen because it demonstrates the value of historical information to aiding the investigation. Furthermore, beyond the scope of the original Terms of Reference, the information from the investigation has been used to develop a GIS-based approach to storing and analysing the information.

7.3.2 The River Wey catchment and river channel management challenges

The River Wey catchment is a southern tributary of the River Thames. The River Wey catchment is bordered by the Mole catchment to the east and the River Loddon catchment to the west. Total catchment area is approximately 1000 km^2 with a channel length of 91 km as defined from the main channel limit of the Wey South

Source	River channel	Comments / Aims of investigation
NRA (1993a)	River Hogsmill	Characterisation of contemporary river channel sensitivity and adjustment
DHV (1995)	Wandle Park Channel	Rehabilitation of the existing channel. Geomorphological design recommendations
NRA (1995a)	River Loddon	Geomorphological implications of removal and/or refurbishment of three mill sites
NRA (1995c)	Edgeware Brook	Geomorphologically sensitive recommendations for proposed revetment works
NRA (1996a)	River Wey	Sedimentation problems associated with the River Wey and Godalming Navigations
GIBB (1997)	Chaffinch Brook	Geomorphologically sensitive channel re-design to replace existing channelised section affected by the Croydon Tramlink Project
Carl Bro Group (1997)	Silk Stream	Failing toe-boarding. Produced a Fluvial Audit to characterise existing channel and target reaches for enhancement
Environment Agency (1998)	River Quaggy	Geomorphological input to channel redesign for proposed flood alleviation works.

Table 7.1 Applied geomorphological studies conducted 1993-1998

Channel	Abbreviation	Upstream Limit	Downstream Limit
Wey	W	SU 873435	TQ 507655
Wey North	WN	SU 725375	SU 873435
Wey South	WS	SU 852321	SU 873435
Cranleigh Water	C	TQ 103360	SU 999464
Tillingbourne	T	TQ 094475	SU 997480
Hoe Stream	H	SU 935516	TQ 046575
The Bourne	B	SU 910631	TQ 065647

* Note: The abbreviation is adopted for reaches in Appendix 2

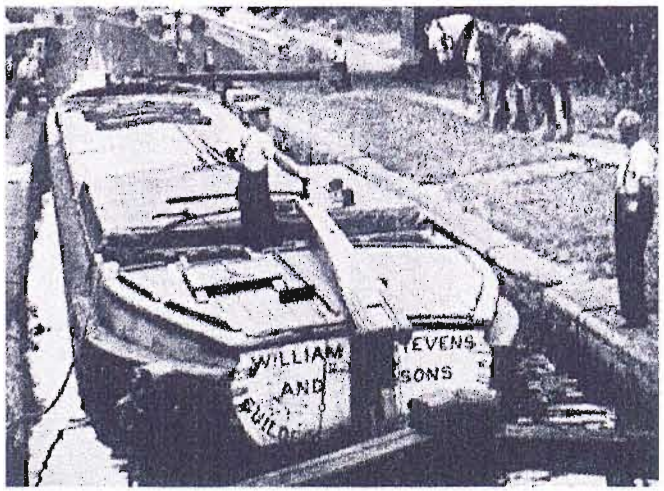
Table 7.2 River Wey channel extents

tributary to the confluence of the River Wey with the River Thames at Weybridge, Surrey. The main channel and six major tributaries have been identified and delimited in Table 7.2.

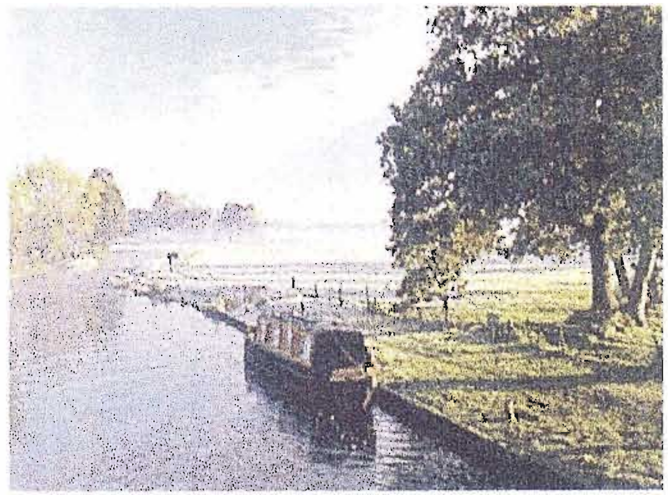
The River Wey has historically served as a navigation route to boat (barge) traffic from the mid 17^{th} Century (Plate 7.1). Boat traffic on the River Wey and Godalming Navigation is dependent on there being sufficient draft between hull and river bed to allow continuous passage. The River Wey Navigation to the north of Guildford is largely based on sands of the Bagshot and Bracklesham Beds. These sediments are relatively easily entrained and transported, forming a sand-bed river channel for the majority of the Navigation length. Consequently sand sedimentation has historically occurred at the confluence of the natural and navigation channels immediately downstream of locks. These sediments have traditionally been periodically dredged (termed 'sand-panning') in order to maintain sufficient draft for the boat traffic. Identification of sedimentation problems and mitigation measures typically relies upon the expertise of channel managers within the Environment Agency and National Trust (present managers of the Wey and Godalming Navigations). NRA (1993b) note that channel maintenance to remove 'excess' sediment is typically based on the assumption that:

a) The river-channel should remain in a condition of static equilibrium and that any sediment remaining is excess and should be removed where this sediment results in the reduction of sufficient draft to allow the boat traffic.

b) The upstream supply of sediment remains constant over time which facilitates a planned schedule of maintenance.



Commercial barge traffic 1950's



Recreational boating 1990's

Plate 7.1 The Wey Navigation past and present

c) Causes of sediment related problems are generally local.

Important to the investigation is the identification of sediment sources and transport through the river-channel. Given that sediment production, transfer and storage are closely linked to channel stability, and that sediment supplied to a given reach may be supplied externally to the reach for which a problem is identified, the identification of reaches exhibiting sedimentation problems should be linked to upstream processes and their relationship to historical Potentially Destabilising Phenomena and contemporary channel conditions.

However, as the use of the Navigation and boat traffic has changed dramatically in the latter part of the 20th Century the Environment Agency is concerned with monitoring the river and Navigation with a view to controlling sediment throughput as a means of improving the efficiency of the dredging operations. In the first instance this will be achieved through an understanding of the river channel's geomorphological characteristics.

The investigation recognises that in addressing this challenge, it is prudent first to identify the precise nature of the river channel change questions asked because this will allow the investigation to target the information requirement and analysis procedures needed to provide satisfactory answers. The geomorphological investigation attempts to identify:

a) Potentially Destabilising Phenomena (PDP) (Sear *et al.*, 1995) and channel response. Historical and contemporary PDP's for the reach and summary of the channel's morphological response to these changes, e.g. has a new equilibrium been achieved / is the channel currently 'active'? This involves the assessment of the nature of the PDP for the watercourse, what reaches are affected and why?

b) Channel stability: Summarises the stability of the contemporary channel form with specific reference to bed and bank erosion and/or deposition, such that, reaches may be identified as potential sediment sources and sediment sinks.

c) Channel sensitivity: Geomorphic sensitivity of each geomorphologically homogeneous reach.

d) Opportunities for enhancement: Consideration is given to geomorphologically sensitive options for river-channel enhancement.

7.4 THE VALUE OF HISTORICAL INFORMATION

7.4.1 Historical information

Examples to date in this thesis have demonstrated the value of historical sources of information to discriminate river channel changes in which the selection of the type of historical information used has been appropriate to the type of problem under investigation. For example, in Chapter 5 suitable cross-section information is used to identify within-channel adjustments for a reach of the River Sence. It is important to recognise however that not all river channel management challenges will be as specific as those illustrated in the proceeding chapters. In this respect, the use of historical sources of information may be multifaceted, using multiple sources of information at a variety of scales. The previous chapters illustrate the potential that some of these available historical sources may be inappropriate, others may be entirely appropriate but not available. Undoubtedly the selection of the sources used will be a compromise and will have a bearing on the investigator's ability to estimate patterns of historical river channel behaviour. However, bringing this information to bear on the investigation adds a further dimension to the geomorphological enquiry and if applied systematically and with respect to the limitations of the material used will yield valuable results to aid the investigation.

A variety of historical sources of information are used to establish river channel change characteristics for the River Wey over extended time scales (see Figure 7.1). In this instance the historical information is used in a supporting role to the contemporary ground-based survey. The questions asked of this survey are not deemed necessary to require a quantitative assessment of river channel change. As such the limitations of the information sources (with respect to their accuracy and resolution) may be relaxed. The reliability of the information is corroborated with reference to field-based investigations and personal discussion with managers and historians concerned with the River Wey catchment.

7.4.2 A GIS-based geomorphological database

The extrapolation of river channel change information is complicated by the wide diversity of information types and formats recorded from both contemporary and historical sources of information. As noted, individual reaches are identified in space; for each reach there are summary information recorded from field survey and these may be supported by various historical information. As such, some information is attributed to the reach, others to the point sources . However, all information was spatially referenced and this allowed for the construction of a GIS-based database as both an archiving tool and as a means of analysing spatio-temporal characteristics of the information.

The GIS-based database uses ARC-INFO GIS. This process is illustrated diagrammatically in Figure 7.1. The set-up of the database allows the mapped information to be linked directly to the attribute information (the database - attribute information is linked by a spreadsheet), for example, Figure 7.2 shows a simplified example for selected values taken from the spreadsheet information.

Historical information may effectively be integrated to this database. ARC-INFO GIS allows for 'Hotlinks' to be included in the analysis. Hotlinks are points that may be spatially referenced and represented on the watercourse. By clicking the cursor on the particular hotlink this will then open an appropriate attribute file. Examples include:

a) Photographic information: The hotlink file may contain a scanned impression of a photographic image representing the river channel at that particular location. Attached to this file may be a series of data indicating the date and time of the photograph, the bearing of the photograph and any accompanying notes. This then allows for singular or series of site-specific photographs to be referenced by their location. Where historical photographs are available (as was the case in Chapter 6 for the River Tillingbourne investigation) these photographs may be stored in this manner and simply viewed on screen in sequence. Video information may be

CATCHMENT INFORMATION

Information type	Information source	Information location identified
Geology	Geological Survey sheets	Kingston University, School of Geological Science
Soils / Landuse	Soil / Landuse survey sheets	Kingston University, School of Geography
Topography / Drainage (Contemporary)	1:10 000 OS sheets	EA, Thames Region (Sunbury)
Topography / Drainage (Historical)	1: 10 560 OS sheets (1st/2nd edition)	Surrey CC, Public Records Office
Mills	Misc. publications Oral discussion	Surrey CC, Public Records Office Surrey Industrial History Group Shere Museum Personal correspondance
Navigation	Misc. publications Oral discussion	National Trust, Wey and Guildford Navigations (Dapdune Wharfe, Guildford)
Flood alleviation / Channel maintenance	Channel maintenance records Oblique photography Oral discussion	EA, Thames Region (Reading and Sunbury)

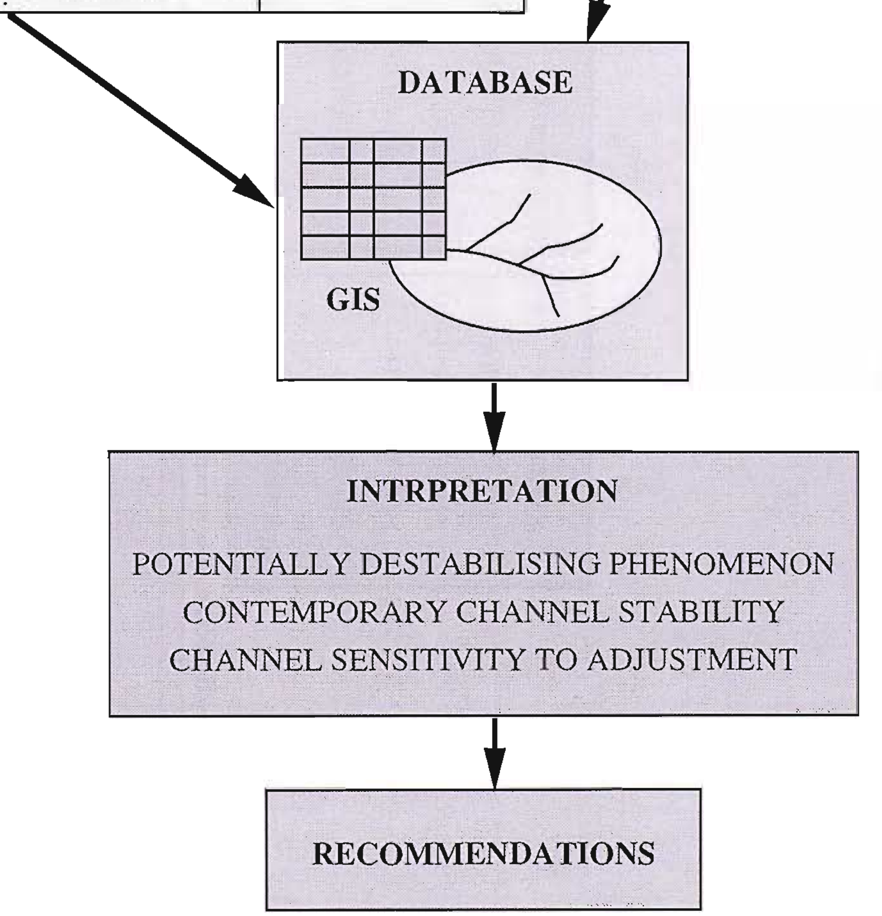


Figure 7.1 Constuction of a GIS-based database for information handling and analysis for the River Wey investigation

Site	*x*	*y*	*BF wdth*	*Low Q width*	*RB Height*	*LB Height*	*Planform*	*Bed*	*Stability*	*Sensitivity*
W (1)	507230	165440	20	-99	2	2	2	2	1	4
W (2)	506850	165440	100	-99	3	2.5	1	2	4	2
W (3)	506430	163920	20	15	1	1	1	2	3	4
W (4)	506160	163580	20	10	1	1	2	3	3	5
W (5)	506900	162910	15	12	3	3	1	3	1	4
W (6)	506940	162730	15	12	3	3	1	3	1	4
W (7)	506950	161400	20	15	2	2	2	4	3	5
W (8)	507070	161300	15	13	2	2	4	3	3	5

Width and depth measurement in metres

Plaform

1 Straight
2 Low sinuosity
3 Moderate sinuosity
4 High sinuosity
5 Braided

Bed

1 Silt / Clay
2 Silt / Sand
3 Sand
4 Sand / Gravel
5 Gravel

Stability

1 Stable
2 Net erosion
3 Composite
4 Net deposition
2 Arteficial

Sensitivity

0 Channleized
1 Low
2 Low
3 Low - Medium
4 Medium - Low
5 Medium
6 Medium - High
7 High - Medium
8 High
9 High
10 High

Figure 7.2 Example of the GIS-based Fluvial Audit spreadsheet

included in a similar manner. For example, by clicking on a hotlink the video view may be played back.

b) Point-based attribute information: For example, cross-section information may be stored as an individual file. By clicking the cursor on the cross hotlink point the cross-sectional information may be displayed. This may include a visual representation of the cross-section as well as any accompanying information.

Hotlink points may be colour coded such that the investigator may recognise all red points as photographs, yellow as cross-sections and so forth.

With the database established the investigator may then make any number of enquires to establish the relationship between the information sources and observe spatial patterns in these data distribution for specific reaches or at a catchment scale. For example:

a) Simple queries, e.g.

- Display all reaches which exhibit a sensitivity >5
- How many Km's of channel have a sand bed?

b) Complex queries, e.g.

- Display all navigable reaches exhibit active enlargement
- What proportion of main channel is channelised and shows evidence of within channel recovery?

Query outputs may be purely visual or may be quantified and the output exported to a statistical software program. Queries may also be made to the mapped image of the channel for example selecting a particular reach will then highlight appropriate attribute information within the database.

7.5 GEOMORPHOLOGICAL RECOMMENDATIONS

7.5.1 Introduction

This section presents a series of geomorphological recommendations on the basis of the specific questions posed in Section 7.2.1.

Individual reach summary information is presented in Appendix 1. Figure 7.3 summarises information for the catchment as a whole represents channel forming events as a time chart.

Sedimentation has been identified over extended reaches of the River Wey. Field evidence supported by historical investigation confirms NRA (1995b) in that many areas of sedimentation are associated with the confluence sections of navigable and non-navigable reaches of the River Wey. However, sedimentation is observed over many additional reaches, including non-navigable upstream reaches of the main channel and tributaries.

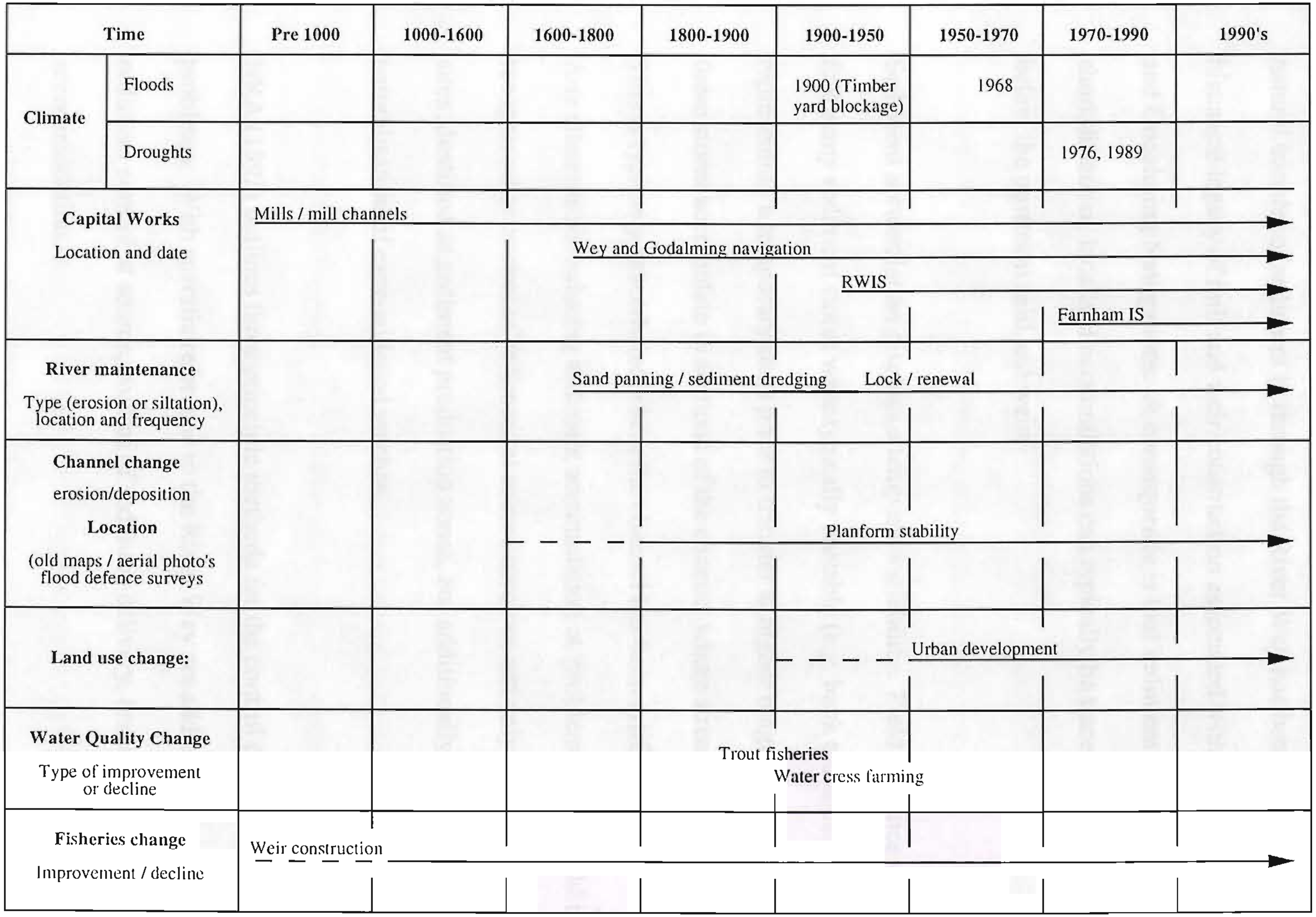


Figure 7.3 Time chart of historical human-induced events on the River Tillingbourne

The transfer of sediment is of key concern to the effective management of sediment related problems identified in NRA (1995b). Field evidence confirms that the natural transfer of sediment in through the River Wey has been interrupted by the historical legacy of mill and weir construction associated with mill sites and the Wey and Godalming Navigations. A consequence is that sediment tends to be routed only short distances, localised accumulations can typically be traced to upstream sources below the upstream mill and weirs

Sediment accumulation displays a temporal variability. Field evidence confirmed that many sediment stores were typically unstable (e.g. bank toe accumulations), representing a temporary store prior to transfer at higher magnitude flows. Many of these stores accumulate in sections of the channel where stream power is reduced. This is typically exacerbated where the channel has been artificially over-widened. Any attempts for reducing sediment accumulation at 'problem sites' should therefore recognise that control of sediment at source involves not only the stabilisation of sites identified as sediment production zones, but additionally encourage the naturalisation of over-widened reaches.

NRA (1992) outlines three principle methods for the control of sediment related problems. With specific reference to the River Wey are addressed by considering sediment control at source, control of sediment delivery, and sediment accommodation.

7.5.2 Sediment control at source

It is noted that in some instances these sources may be identified over short localised reaches which, given their limited spatial extent, may be targeted for stabilisation. The means of stabilisation is somewhat site specific, dependent on the nature of the eroding channel and an individual detailed appraisal of the geomorphological implications of such action. Geomorphologically sensitive measures are advocated where appropriate in order to maintain and, where applicable, enhance geomorphic diversity. It is accepted in certain cases this may be inappropriate in these cases it would be advantageous to consider 'hybrid' alternatives (NRA, 1996b).

Sedimentary sources on the River Wey may be identified within reaches of moderate to high geomorphological diversity. Typically within these reaches, sediment production can often be observed over extended distances and not to any one individual site. However, in these cases, sediment production is typically balanced by sediment deposition within the same reach.

Erosion control can additionally be attributed to other activities. Addressing the cause rather than the symptom may provide longer term mitigation. Recurring examples on the River Wey include:

a) Cattle poaching: Cattle were seen to have unrestricted bank access in many rural reaches of the River Wey. Restriction of bankside access would reduce the physical stress on the banktop and encourage the growth and diversity of bankside vegetation. Where cattle are allowed to cross the channel and drink at the bankside, then these areas may be cordoned off to the rest of the reach.

b) Towpaths: The opportunity exists to restore riparian vegetation on the channel banks adjacent to the towpath along selected reaches of the channel. This would enhance the stability of the channel and restrict direct public access to the bank, reducing banktop erosion at vulnerable sites. Public amenity / recreation could be maintained through the selection of appropriate species. This may have knock-on effects of improving public safety.

7.5.3 Control of sediment delivery

As before-mentioned, sedimentation problems on the River Wey can typically be linked to upstream sources. However, in instances where the modification of the upstream sources is inappropriate sediment delivery to the problem area may be addressed.

For example, the upstream natural channel from the Yvonne Arnault theatre in Guildford is one such reach where sedimentation occurs at the confluence of the navigable and non-navigable channels. Sediment supply can be attributed to channel erosion from the immediate upstream natural channel. Given that slope stabilisation options are unadvised given the natural bankside vegetation, two possible options exist involving the control of sediment supply:

a) Trapping a proportion of the sediment in the downstream limit of this reach through the use if sediment traps.

b) Reduction of the stream power through this reach by either, increasing down channel length and/or meander re-instatement, or, provision of a series of shallow weirs to step the water through the channel and provide for localised sediment trapping.

7.5.4 Sediment accommodation

This involves the accommodation of peak sediment delivery within the channel through recognition of temporal variability of storage. In practical terms, sediment accommodation for the River Wey may be achieved in part by the recognition and preservation of sites which display geomorphic diversity and through the encouragement of sites which show naturalised recovery to imposed conditions.

Numerous reaches of the River Wey and tributaries show evidence of channel over-widening and toe/berm sedimentation. Opportunities exist for the enhancement of these sites through the reduction of low-flow width. Methods employed are somewhat site specific but may include the judicious use of groynes, flow diversion and vegetation.

7.6 CONCLUSIONS

Historical sources of information provide a valuable resource to applied geomorphological investigations. Through examples illustrated in this thesis it may be demonstrated how specific types of geomorpholgical problem may be effectively associated to particular types of historical information. In this chapter it was important to demonstrate that historical information must be chosen appropriately for specific river channel change questions. The example of the River Wey illustrates this point effectively. There is no one single question that is asked but rather a series of questions. It is impossible to answer any of these questions with reference to the historical information alone. It is possible to answer these questions from contemporary observation alone, but the confidence in these recommendations (proposed in Section 7.4) is greatly enhanced through the contribution of the historical information. The historical information provides corroboration for the contemporary field observations, but also serves to effectively direct the field investigation to specified points of interest.

The nature of the qualitative historical contribution is impossible to determine in terms of its overall benefit to the enquiry and recommendations; the contribution is intangible in the sense that it is impossible to quantify this contribution. Certainly, the contribution to this study and similar studies has risen to the challenges posed in section 7.2 - the application of this information to aiding applied geomorphological research.

7.7 SUMMARY

Geomorphology has great potential for aiding applied research disciplines but must meet a series of challenges where geomorphological expertise is to be applied effectively to river channel management.

Applied geomorpholgical studies have already demonstrated their value aiding river channel management. The River Wey example provides one such example where a suite of contemporary and historical information may be used in combination to explore a specific management challenge.

Computer-based information handling and manipulation software offer tremendous potential for aiding the analysis of diverse formats of geomorphologically related information and communicating this information with maximum efficiency and minimal information loss to a non-geomorphologically trained audience.

CHAPTER 8

THE CONTRIBUTION OF METHODS OF HISTORICAL RIVER CHANNEL CHANGE RECONSTRUCTION TO APPLIED GEOMORHOLOGICAL RESEARCH

8.1 INTRODUCTION

Previous chapters have considered the value of historical sources of information for providing a means of extrapolating river channel changes at a variety of spatial and temporal scales. Chapter 2 asks a series of river channel change questions (based on Gregory (1987)) as a means for evaluating the ability of historical information to provide answers which are relevant and significant to river channel change questions. In this respect the ability of the historical sources of information to fulfil these requirements is dependent on their availability, resolution (in space and in time) and their accuracy. Chapter 3 considered the accuracy of historical sources of information in detail and considered that their accuracy is as much dependent on the demands placed upon the analysis of the information and the operational procedures used to extrapolate river channel change information as the inherent errors in the historical sources of information themselves. However, Chapter 3 demonstrated that if the analysis procedures are able to evaluate the nature and significance of the components of inherent and operation error as they are propagated at each stage of the analysis then the investigator may be able to estimate the Total Error. This estimate may itself be somewhat conceptual because of the perceptual, subjective and dependent nature by which river channel change information may be collected an analysed. In certain cases surrogate values may be estimated and used to estimate the magnitude of individual or amalgamated component errors and allow the estimate of a more quantitative estimate of Total Error.

Chapters 4, 5 and 6 provide three methodologies for extrapolating river channel change from planform, cross-sectional and ground-based photographic sources respectively. In each example the confidence in the estimate of river channel change may be attributed to the nature of the questions being asked of the enquiry and to the estimate of the Total Error. As such the resolution of the historical information may be demonstrated to be suitable to closely match the nature and scale of the river channel change.

Chapter 7 illustrated that historical information may constitute an integral part of applied geomorphological research to aid river channel management decisions. The study presented in Chapter 7 considers how various historical sources of information may be used in combination with contemporary survey information to provide an invaluable aid to extrapolating river channel change at a catchment scale. This chapter highlights the importance of the ability of the investigator to interpret several differing formats of information with varying accuracy in to one conceptual historical model of change.

The aim of this chapter is to return to the series of questions highlighted in Chapter 2 and to discuss how the lessons of the methods and examples illustrated in this thesis may move towards answering these questions. Specifically, this chapter will investigate:

a) The challenges remaining for the geomorphologist given the limiting abilities of the historical information and the methods of analysis to provide answers to river channel change questions.

b) Further research opportunities.

8.2 RECOMMENDATIONS

The evaluation of Total Error has shown that there are limits to which any one of the techniques may be used. Chapter 2 observed that the resolution of the historical information must be appropriate for the nature of the river channel change. In applied geomorphological research this scale might be anticipated from the nature of the specific questions asked and the investigator must see fit to choose information sources which are fitting to the enquiry.

A series of stages may be envisaged as a basis for achieving these aims:

Stage 1 - River channel change questions

What are the questions being asked of the applied research? The investigator must establish the scope of the enquiry and the level of 'detail' required of the answers. Establish how historical information may be beneficial to the enquiry and the perceived role of the historical information to the enquiry.

Stage 2 - What are the anticipated absolute magnitude of river channel change and the absolute physical size of the river channel?

This will determine the anticipated scale of river channel adjustments. The resolution of the historical information to address these changes must be selected appropriate to these anticipated scales of adjustment. In this instance, the ability of the investigator to 'anticipate' is based on experience, which may be augmented with a pilot investigation to gain first hand experience prior to choosing particular methods of analysis.

Stage 3- What is the maximum acceptable Total Error in order to distinguish river channel changes with confidence?

Given the demands imposed by the river channel change questions, the size of the river channel under investigation and a qualitative notion of the anticipated rate of river channel adjustment the investigator must decide the level of confidence to which the historical investigation may aid the enquiry. Certain investigations will require the estimation of quantitative indices of river channel change, in these cases a greater demand is placed in the information to provide results whose estimates are not exceeded by the Total Error in the estimation of that estimate. Otherwise, more semi-quantitative and qualitative estimates may relax the demands concerning Total error, yet still provide estimates to a similar degree of confidence.

Stage 4 - What spatial and temporal resolution is required in order to achieve this level of confidence?

When the anticipated scale of adjustment and maximum permissible error established the investigator must decide the level of resolution required to extrapolate river channel change. This resolution must be appropriate:

a) The spatial resolution must be sufficient that the investigator is able to discern features of interest precisely. As the investigation approaches the limiting resolution so the inherent errors of the historical information become more apparent.

b) The temporal resolution must be such that the investigator is able to discern river channel changes between temporally successive information. In this respect also, the period of the historical record must be appropriate. For example, an investigation to extrapolate river channel change as a consequence of a specific dated disturbance would ideally require information pre-dating and post-dating the disturbance.

Stage 5 - What sources of information exist at this level of resolution?

This stage involves the choice of the appropriate historical information with which to address the historical analysis, Ideally, the investigator will have the option to choose the format of the historical information required at the desired resolution and for the desired period. In practice, such information is seldom available and the investigator must seek to compromise between the available information and the requirements of the investigation:

a) Historical information may be rejected on the basis that it will not fulfil the requirements of the investigation to a desired level of confidence. The investigator must seek an alternative means of analysis.

b) The level of confidence of the results of the historical analysis is compromised in order to accommodate the available historical information. This need not compromise the overall confidence in the investigation as a whole if alternative means of answering the river channel change question may be found. The historical information may be used in a qualitative manner to support alternative methods of analysis.

c) The channel change questions are modified in order to accommodate the available information.

It must be remembered that where the investigator may undertake the analysis with information that is not able to discern river channel change then this result is still valid as long as the context of the results is stated. For example, the analysis of river channel planform change for the River Sence using 1:10000 scale Ordnance Survey sheets in the same manner as the River Towy investigation will estimate that the River Sence maintains its planform stability over extended reaches. However, the confidence of this result is now understood such that the investigation may still be said to yield information with regard to river channel change. In this case, 'the investigation concludes that there is sparse lateral adjustment over the investigative period which may confidently exceed a given lateral displacement for a given level of confidence.' Understanding the limitations of the resolution and accuracy are therefore not only useful to define the limitations of approaches to extrapolate river channel change, but also allow the investigator to qualify the interpretation of river channel stability.

8.3 LINKS BETWEEN MANAGEMENT AND HISTORICAL GEOMORPHOLOGY

8.3.1 The present

Chapter 2 introduced the notion that the complexity of a feature is a function of its size and the scale at which it is observed. Not unsurprisingly, the greater the complexity of a feature then the poorer the ability of historical information to provide answers to river channel change questions. Increasing complexity yields greater indeterminacy in river channel change and therefore decreases the ability of the geomorphologist to estimate patterns of future river channel behaviour. Chapter 2 observed that Schiedegger (1967) noted that if it were possible to provide sufficient detail (resolution) it should, in theory, be possible to unravel these complex relationships. When dealing retrospectively with historical information this level of detail is already established in the inherent characteristics of this information. Without supporting or corroborating information the historical information will never be able to surpass these inherent limitations. As such, while historical techniques will continue to improve the capacity to interpolate past change, these values will always remain estimates of true river channel change values.

Understanding these limitations is important to the effective application of historical geomorphological investigations to river channel management:

a) Acceptance that because it will never be possible to disseminate past changes to 100% accuracy at 100% resolution then it is impossible to predict future river channel behaviour to this level of confidence.

b) River channel stability is scale dependent in space and time. River channel instability does not immediately imply a river channel management problem. Historical geomorphology addresses patterns of non-linear behaviour and provides insights into controlling processes. Understanding both patterns and processes of behaviour in the past provides a unique standpoint from which to address potential future change.

c) Historical geomorphology provides the river channel manager with a suite of techniques to estimate the likely impact of river channel management decisions through an assessment of the propensity (sensitivity) to change at a given scale and the likely 'direction' that patterns of adjustment will adopt.

River channel management attention in the UK is recognising the value of geomorphological information at a variety of scales. Historical geomorpholgy has already been used effectively as an aid to these studies. This thesis makes an important contribution in this respect in that it addresses key issues to ensure that the links between management and historical geomorphology are used appropriately. The benefits of geomorphologically sensitive approaches to river channel management (e.g. river restoration, rehabilitation and enhancement) are now clearly established. Systematic application of the historical techniques, such as those illustrated in this thesis, will further enhance this potential.

8.3.2 Further Research Opportunities

River channel management investigations of river channel change have illustrated the importance of being able to communicate the findings of the investigation effectively. As such, the estimation of Total Error may be considered to transcribe beyond the extrapolation of river channel change indices and extends to the ability of the geomorphologist to communicate information with maximum efficiency and minimal information loss to those who will make river channel management decisions. The ability to represent the findings of the investigation clearly and concisely is important. Further research will investigate the potential of digital based information to fulfil this role.

One of the key ways in which geomorphological contributions to river channel management may be addressed is to consider how information may be collected in future. If information may be collected at a desired resolution in space and in time this will provide the geomorphologist with a useful tool for assessing future adjustments.

Further research stemming from this thesis has investigated the application of airborne videography and digital imagery as a means of collecting river channel information. Digital image collection is helpful in that it overcomes a stage of information analysis in that the digital representation may be input directly into the analysis. The definition of the river channel boundary location may be made directly on screen. Imagery may be collected at a specified resolution. For example, a planform study, which requires the definition of features of a given size, may obtain information at this resolution through pre-determining the flight height, choice of pixel array and lens parameter. All information which is collected is geo-referenced at the moment of collection. The use of a Global Positioning System receiver located within the plane/helicopter allows the position of each individual frame to be located in space. Precise flight heights are recorded in tandem through pressure altimeters or radiometrically from the airborne platform. The digital imagery can be manipulated effectively. Using an image processing software the individual frames may be balanced between the wavebands to select representations of the channel which best define specified river channel features. Images may be rectified in the same manner as is suggested for the planform methodology. Images may be effectively montage together to produce continuous seamless images. This information may form a valuable level of a GIS-based database to provide the river channel manager with an aerial perspective.

APPENDIX 1

SELECTED HISTORICAL RIVER CHANNEL CHANGE STUDIES INDICATING ADOPTED METHOD/S OF RECONSTRUCTION

Date	Author/s	Comments
1962	Carr	On historical accuracy not river cc study in itself
1967	Johnson and Paynter	Maps, planform change
1969	Carr	Orford spit (coastal) example - use of maps from 1530
1972	Alexander and Nunnally	Maps, planform change
1972	Hammer	Cross-sections 78 streams, urbanisation space for time
1973	Knighton	Historical erosion study
1973	Mosely	Air photographs and maps 100 years of change
1974	Brice	Maps, meander migration and historical stability
1974	Gregory and Park	Space for time substitution methods
1975	Anderson and Carver	Historical ground based photographs from 1952
1975	Ferguson	Meander paths – may be determined from historical information
1976	Gregory and Park	Space for time, gulley evolution
1976	Gregory and Park	Space for time, rivers of north west Yorkshire
1976	Hollis and Luchet	Space and time, Canon's Brook (later criticised)
1976	Hooke and Perry	Accuracy of maps
1976	Lewin	Repeat surveys and air photos - high temporal resolution
1977	Graf	Historical plus dendrochronology
1977	Hooke	Maps, air photographs , Devon rivers
1977	Petts	Space for time and Dendrochronology
1977	Lewin and Weir	Maps, air photos and photogrammetry
1978	Lewin	Traditional maps, air photographs and ground surveys
1978	Newson and Harris	Link in with Newson 1979
1979	Graf	Space for time and oblique channel photographs
1979	Newson	"Continuous" monitoring
1979	Petts	Response to regulation
1980	Newson	Air photos used for flooding 1973 with field based survey
1980	Overdon and Gregory	Historical river channel network analysis
1980	Petts	Historical methods, scale considered
1981	Blacknell	Air photographs and ground-based survey
1981	Overdon	New Forest study, maps and channel network
1982	Bernard and Melhorne	Air photographs
1982	Blacknell	Air photographs and ground-based survey
1982	Gregory and Maldew	Review
1982	Milne	Air photographs and maps
1982	Thorne and Lewin	River Severn - maps and air photographs, erosion pins
1983	Gregory and Brooke	Large scale maps cross-sections
1983	Hooke and Harvey	Maps and air photographs
1983	Lewin *et al.*	Ystwyth traditional and air photographs etc.
1983	Lewis and Lewin	Maps, air photographs etc classic investigation of several rivers
1983	Murgatroyd and Ternon	Erosion pins and mapping
1984	Graf	Maps - probabilistic approach
1984	Lewin	Maps
1984	Newson and Leeks	River Towy erosion study
1985	Burrin	Ouse (Brighton) very old human activity
1986	Carson	Air photographs (40 years) Contemporary re-survey (1982 - 1984)

Appendix 1 Selected historical river channel change studies indicating adopted method/s of reconstruction

1986	Hooke	Continuous records (including oblique photographs)
1986	Lewin and	Towy maps and air photographs use photogrammetry too
1986	Nanson and Hickin	Air photographs only 21-33 years
1986	Thompson	Maps and air photographs (used in supporting role for shorter term changes) Skirden, Beck
1987	Gregory	"Comparative" study - summary of global and UK papers
1987	Harvey	Continuous records
1987	Newson and Leeks	Scale considerations – management examples
1987	Simon	Surveys (short, 5 years) and Dendrochronology, relaxation to disturbance
1987	Smith	Maps and air photographs
1987	Smith	Maps and air photographs
1987	Thompson	Classic maps and air photos Longdon Brook
1988	Dalton and Fox	Map overlay
1988	Leeks *et al.*	Cross-sectional re-survey, information used in conjunction with other techniques
1988	Neller	18 months erosion pin study, urban Australia rivers
1989	Knighton	Relative heights of bridges where bridges are dated
1989	Leeks and Newson	Re-survey and short-term historical responses
1989	McEwen	River Dee - Scotland - maps 1750 catchment appraisal
1989	Petts	Review and perspectives
1989	Roberts	Space for time substitutions
1990	Brizga and Finlayson	Survey and air photographs
1990	Hooke *et al.*	Integration of historical with sedimentary
1990	Cox	Cross sectional records 1956/1970/1990
1991	Ebisemiju	Space for time substitution review
1991	Graf,(J.B.) *et al.*	Sediment records only - Colorado River
1991	Gregory *et al.*	Field survey
1991	Lawler	Continuous monitoring using PEEP's
1991	Sherad and Erskine	Changes from dam - long section and cross section - sectional change
1991	Sherrard and Erskine	Cross sections 1976 and 1984 and ground-based photographs
1991	Trimble and Cooke	Methods non-specific
1992	Darby and Thorne	Change by space for time subs
1992	Erskine	Hinter River map based surveys
1993	Norbergen	Landsat MSS and TM imagery large spatial scale change
1993	Wyzga	Poland rivers air photograph study
1994	Benn and Erskine	Cross-sectional re-survey (sites marked)
1994	Davis and Gregory	Long term morphological monitoring
1994	Downs	Historical maps used as secondary information source
1994	Gurnell *et al.*	Maps and aerial photographs
1994	Lane *et al*	Short temporal scales, photogrammetric approaches
1994	Warner	Hawkesbury River maps, air photographs, cross sections
1995	Ashbridge	At a site - cross-section
1996	Friedman *et al.*	Dendrochronology
1996	Gomez and Merron	Air photographs planform maps used to determine slope
1996	Gurnell et al	Air photographs River Dee
1996	NRA	"Continuous" 2 year monitoring of bank erosion

Appendix 1 (Continued) Selected historical river channel change studies indicating adopted method/s of reconstruction

APPENDIX 2

RIVER WEY REACH SUMMARY INFORMATION

REACH SUMMARY INFORMATION - RIVER WEY

Reach location	Site/s	PDP / Response	Channel stability	Channel sensitivity	Opportunities for enhancement
Thames confluence - Weybridge.	W(1)	Flood alleviation - channel over-widened. Sittation at bank toe to LB.	Moderate. Localised BP to R/B for boat moorings.	Low - moderate (3-4)	Provision of vegetative buffer to L/B.
Weybridge	W(2)	Weybridge lock - channel modification, over-widened. Siltation within channel. Sand bar accumulation at U/S of Bridge Rd bridge.	Moderate. Maintained through periodic dredging. Channel banks stabilised through localised protection (sheet piling).	Low - moderate (3)	
Weybridge Lock - Brooklands	W(3)-W(4)	Channel extensively straightened. Channel response by over-widening. Contemporary salutation at bank toe.	Moderate. Bank stabilised through vegetation. Contemporary change limited to more sinuous reaches (e.g. W(4)). sedimentation from locally derived material.	Moderate (4-5). Greater diversity than D/S reaches.	Bank erosion enhanced through cattle poaching adjacent to Addlestone jct. Protective buffer / fencing.
Brooklands	W(5)-W(6)	Channel re-sectioned with localised re-alignment). Minimal response, minor a bank toe.	Moderate - High. Very little change / response observed.	Low (2-3). Minimal diversity. Absence of naturalised form.	Increase diversity (meander reinstatement ?). Vegetation increase, shade.
Weymede - Byfleet Mill	W(7)-W(10)	D/S response to Byfleet mill. W+ Gravel bar accumulation.	Low - moderate. Clear evidence for lateral erosion. Incision minimal due to gravel armour. localised BP (e.g., W(7a) and W(8).	Moderate - High (5-7). diversity encouraged by gravel bedforms.	Favour 'do nothing' option D/S from mill pool (TQ 0707 6130)
U/S Byfleet Mill - M25	W(11)	Re-sectioned channel at M25. Siltation - formation of berm, stabilised along R/B.	Moderate. Prevalent adjustment. Erosion potential reduced in backwater reach U/S from Byfleet mill	Moderate (4). Minimal diversity.	Further encouragement for berm stabilisation, channel width reduction
Wisley	W(12)-W(14)	Recent bank protection at Wisley golf course. Stabilisation of eroding bank.	Poor - moderate (where protected). Unprotected reaches show vertical erosion faces. Sediment source for bar accretion - flow diversion.	Moderate - High (4-6). Greatest in wooded reaches .	Vegetative buffer, restriction of access from golf course.
Newark Lane - D/S Stoke Mill	W(15)-W(21)	Minimal alteration, non-navigable 'natural reaches' through Send parish Response of channel to Mill and navigation locks localised. Flow velocity decreased through backed up water.	Moderate - High throughout extended reach. Minimal BP. Banks show some evidence of adjustment, slumping and toe accretion at given locations (see Appendix A)	Moderate (4-5). Diversity reduced by inactive channel where water backed-up)	Localised erosion exacerbated by cattle poaching, e.g., W(15)/W(16)
Stoke Mill - B&Q site, Guildford	W(22)-W(23)	Backwater of Stoke Mill, minimal stream power, channel over-widened. Navigable channel. Response through sedimentation from bank.	Moderate - Sedimentation, bank modification at B&Q site and adjacent residential properties throughout reach (L/B).	Low - Moderate (3). Minimal diversity, channel activity low.	Provision of vegetative buffer to R/B along FP aid stabilisation of sediment accumulation.

Guildford: Dapdune wharf - Y.Arnault Theatre	W(24)-W(26)	Maintenance for navigable channel. Over-widened, backwater reach to lock at W(26). Sedimentation problems recorded within channel reducing navigation potential.	Moderate - High: Minimal erosion, localised to where banks over-steepened and unprotected. Sedimentation at bank toe of non-canalised reaches.	Low (1-3) - Extensive modification has reduced diversity (e.g., W(25))	Minimal opportunity given floodplain development.
U/S Y. Arnault Theatre	W(27)	Reach immediately D/S from weir: W+, D+	Low - Clear evidence for lateral erosion and vertical incision. Release of sediment which is transported D/S to Y.A. Theatre	Moderate - High (5-6)	Investigate potential for gravel traps to minimise D/S sediment delivery to Y.A. Theatre.
Shalford (SSSI)	W(28)	Minimal alteration. Non navigable channel.	Moderate - Naturalised bank erosion and point bar sedimentation within sinuous reach.	Moderate - High (6-7)	'Do nothing' status as SSSI favoured.
Broadfield	W(29)	Water backed up from St. Catherine's Lock: Over-widened channel, minimal response. Sedimentation potential at confluence with Cranleigh Water, may reduce navigation potential if unchecked.	Moderate - High: minimal activity in low energy channel. Low flow depth at confluence - sediment accumulation.	Low - moderate (4). Minimal diversity, lacks vegetative buffering.	Buffer vegetation to RB.
Peasmarsh - Cattershall	W(30)	Minimal alteration. Non navigable channel.	Low - moderate: Naturalised bank erosion and sedimentation. Channel incision leaving vertical erosion faces. Shallow riffles.	Moderate - High (6)	Sediment production zone - ideally to be left to itself. excess sediments could be shoaled / use of gravel traps.
Godalming: Cattershall - Westbrook	W(31)-W(34)	Water backed behind weir throughout reach. Channel over-widened. Cattershall flood cut: Channel erosion, degradation of bank protection structures	Moderate - Minimal energy channel. Favours sedimentation, particularly near Sainsbury's where flow depth particularly shallow. Cattershall flood cut: Low stability.	Low - Moderate (3-5). Variable, increasing at Riverside walk where less bank constraint.	Bank protection requirement to Cattershall flood cut. Opportunities for channel narrowing and increased diversity at Riverside walk.
Westbrook - Lower Eashing	W(35)-W(41)	Minimal alteration. Flow backed up in D/S end of reach. Localised bank protection, e.g., Weir to Hell Ditch (SU 9630 4434)	Moderate - Channel energy increases in upstream direction. Naturalised erosion and deposition through SSSI. Within channel sedimentation immediately D/S of Eashing mill.	Moderate - High (6-8). Morphological diversity, High at 'Thundery Meadows'	'Do nothing' option favoured for most of the reach. Encouragement of bankside vegetation. Cattle access restriction.
Lower Eashing - Tilford	W(41)-W(48)	Alteration through mill/weirs: Over-widening of channel at A3 bypass, Somerset bridge, Tilford bridge. Channel response variable dependent on stream power related to backed flow.	Moderate (variable) - Erosion specific to sites identified in Appendix A, Vertical erosion faces observed, particularly where channel incised. Sediment deposits limited to bank toe. Tilford: Erosion immediately D/S from bridge, sand accumulation at bridge piers.	Moderate - High (6-7). Lacks diversity of previous reach, particularly in over-widened reaches.	Encouragement of return to low-flow width (flow deflection ?). Stabilisation of sedimentary assemblages at bank toe.

REACH SUMMARY INFORMATION - WEY NORTH

Reach location	Site/s	PDP / Response	Channel stability	Channel sensitivity	Opportunities for enhancement
Tilford - Farnham	WN(1)- WN(2)	Alteration through Mill/weirs (Tilford mill and Waverley mill): Channel response has achieved new equilibrium form	Moderate - Evidence of bank erosion and deposition, but contemporary change appears minimal. Stabilisation of banks through vegetation. Localised BP, e.g., WN(1)	Moderate - High (7-9). Diversity of channel condition. Gravels provide armour below weirs. Pool-riffle evidence.	Encouragement of bankside vegetation. Minimal maintenance favoured. Preservation of bedforms.
Farnham: D/S - Passmore bridge	WN(3)- WN(6)	Farnham Flood Alleviation Scheme: Extensive re-sectioning of channel. Localised bank protection, e.g., South St. bridge. Channel response: Sedimentation along bank toe, bar development (e.g., WN(5a)).	Moderate - High: Banks graded by re-sectioning. Localised bank protection. Concrete trapezoidal section at South St. bridge. Adjustment largely a response to over-widening through sedimentation.	Low - moderate: (1-4). Constraint by scheme, shows minimal natural re-adjustment.	Investigation of options for narrowing the low flow capacity.
Passmore bridge - Alton	W(7)-W(11)	Alteration through mill/weirs: Channel has responded by achieving new equilibrium form. Instability possibly attributed to localised influences.	Moderate - High: evidence of localised bank slump, particularly D/S from Turks mill. Bed becomes more naturalised - gravels and flints of the chalk further U/S. Sedimentation where over-widened e.g., WN(11).	Moderate - High: (6-8). dependent largely on proximity to mill site. Bed diversity through gravel pool-riffles	Encouragement of buffer vegetation to stabilise banks. Restriction of cattle access.
Alton	W(11)	Bank regrading, possible over-widening: sedimentation to restore low flow width.	High: No evidence for bank failure observed. Bed stability through gravel armour achieved.	Moderate (5): Whilst over-widened still maintains bed diversity.	Restoration of low flow width - possible use of groins.

REACH SUMMARY INFORMATION - WEY SOUTH

Reach location	Site/s	PDP / Response	Channel stability	Channel sensitivity	Opportunities for enhancement
Kingsley Stream	WS(1)	None identified: Channel in naturalised condition. Minor localised modification, e.g. remedial bank protection (and failure).	Moderate: Channel incision, vertical bank failure recorded. Sedimentation from local sources.	High (8-9): Naturalised stream showing marked morphological diversity	Minimal. Management works should attempt to maintain natural character.
Oakhanger Stream	WS(2)-WS(3)	Localised disturbance at Gibbs lane. Channel remains largely in naturalised condition.	Moderate: Channel incision, slumping of material to toe. Sedimentation of gravel bed to riffles.	High (8-9): High diversity of form. Degraded locally, WS(3).	Restoration of degraded section/s.
Oxney Stream (at Sleaford bridge)	WS(4)	Local re-sectioning of channel to Sleaford bridge. Minimal channel response, minor sedimentation.	High: Minimal activity.	Moderate (3-5): Minimal diversity in re-sectioned channel.	
Pitt Farm	WS(16)	None identified: Naturalised channel condition.	Moderate - High: Sinuous course, moderately low energy channel to confluence at Tilford.	Moderate - High (6-8). Diversity restricted by lack of riparian vegetation.	Encouragement of riparian buffer vegetation. restriction of cattle access to channel.
D/S from Brockford bridge	WS(15)-WS(14)	None identified: naturalised channel condition.	Moderate: Channel banked to sandstone bedrock WS(15) - vertical erosion face providing channel sediment. Stabilisation through riparian vegetation. Over-widening of channel immediately D/S of weir at Hantingford bridge. Within channel sediment accumulation.	High (7-9): Naturalised channel, pool-riffle sequence evident.	Minimal maintenance advocated.
Linstead	WS(6)	None identified: Naturalised channel condition.	Moderate - High: Semi-naturalised floodplain, minimal bankside trees. natural instability observed through vertical bank failure, point bar sedimentation.	Moderate - High (6-8): Naturalised bed forms.	Increased diversity of bankside vegetation aiding stability of eroding bank.
Olivers farm - Liphook	WS(7)-WS(13)	Minimal: Channel appears over-widened in section immediately D/S from weir WS(11), otherwise in semi-naturalised condition throughout reach.	Moderate - High: Minimal evidence for bank or bed erosion. Banks well vegetated throughout reach. Minor toe sedimentation. Backwater effect behind weir (WS11). Gravel bedforms in U/S section of reach provides bed armour.	High (7-9): Channel diversity maintained. Flow variability through shallow bed, particularly U/S section of reach.	Minimal maintenance advocated. Preservation of sediment throughput.

REACH SUMMARY INFORMATION - TILLINGBOURNE

Reach location	Site/s	PDP / Response	Channel stability	Channel sensitivity	Opportunities for enhancement
Wey confluence	T(1)-T(2)	Channel widening ? (unconfirmed): Toe sedimentation.	Moderate - High: Low energy channel, favouring sediment deposition. Banks stable.	Moderate: (4-5): Minimal flow variability, lack of bedform.	Restoration of low flow width ? Difficult considering minimal gradient channel.
Shalford	T(3)	Channelisation for approx. 100m D/S from The Street bridge. Recent bridge modification: Negligable channel response.	High: No evidence for failure of channelised section. No excessive sedimentation.	Low (1): Channelised reach.	Minimal without structural change to channelisation.
Shalford - Chilworth	T(4)-T(5)	Increased stream power in U/S section immediately below weirs to north and south channels.	Moderate - High: Channel incision in U/S section preventing lateral erosion, banks steep but remain stable - trees. Localised BP in D/S section where backs residential property.	Moderate: (5-6): some diversity of bedform. Dense vegetative buffer in U/S section.	
Chilworth mill race channel. (southern)	T(6)-T(7)	Mill (gunpowder works). Re-sectioned channel: Sedimentation through lack of available stream power. Channel over-widened for sweetened flow.	Moderate: Minimal activity due to low gradient.	Moderate: (4-5): Lacks diversity.	Reduction of lowflow width - shallow groins. Drop base-level at D/S limit to increase gradient.
Chilworth (main channel)	T(8)	Mill race diversion/weir: Channel achieved morphological adjustment to imposed conditions.	Moderate - High: Banks steep but generally stable (clay matrix). Gravel bed forms effective armour layer.	Moderate - High (6-8): Pool-riffle sequence observed, abundance of riparian vegetation.	Minimal, preservation of naturalised morphological diversity.
* Mill	T(9)	Mill: Flow backed to BF. Minimal gradient, low energy. Deposition of fines	High: Banks graded very shallow to low flow depth, minimal opportunity for sediment entrainment given stream power.	Low - moderate (3-5): Minimal flow variability. lacks bedform diversity .	Reduction of low flow width, stabilisation of toe sediments.
Vale End fishery	T(10)	Channel ponded to provide fishery. No response observed locally.	High: insufficient energy for geomorphic adjustment. Lake sedimentation assumed, but unable to confirm.	Low (1-2)	
Albury	T(11)-T(13)	Mill/weir modification, localised channel modification backing to residential property.	Moderate: Banks demonstrate evidence of failure, particularly where unprotected, but heights generally low. Bed remains stable, armoured with flints set in sandy clay matrix.	Moderate (5): Despite bank protection, maintains naturalised bedform.	Judicious protection of failing banks.
Albury - Shere	T(14)-T(15)	Mill/weir modification: Sedimentation in U/S reach where flow is backed up. Channel adjusted to imposed conditions. Localised channelisation at Shere.	Moderate - High: Banks generally stable throughout. Minor instability at Shere through unrestricted public access.	Moderate - High (6-8): Channel diversity, bedforms in U/S sections.	Minimal heavy maintenance advocated.

REACH SUMMARY INFORMATION - CRANLEIGH WATER

Reach location	Site/s	PDP / Response	Channel stability	Channel sensitivity	Opportunities for enhancement
Shalford	C(1)	Weir: W+ immediately D/S from weir - sediment source to D/S section , but no obvious sedimentation. Transport to Wey?	Moderate (Low at weir pool): Mill pool show evidence for channel enlargement, through bank recession. Stability of D/S channel to confluence improved.	Moderate (4-6): Lacks bedform diversity.	Localised protection to weir pool
D/S from Run Common	C(2)-C(4)	Possibly over-widened locally: Sedimentation within channel e.g. C(2).	Moderate: Bank stability variable, more sinuous reaches show vertical erosion faces, slump of bank material, e.g. C(4). Widespread sedimentation, both at bank toe and within channel.	Moderate - High (5-7): Cohesive sediments increase bank strength. diversity through flow variability.	Minimal. Possible stabilisation of bank toe locally and possible reduction of low flow width where channel appears over-widened.
Whipley Farm - Knowle Lane	C(5)-C(9)	Minimal. Shallow weirs impose localised control. Possibly over-widened locally.	Moderate: Sedimentation dominates through much of the reach. Width reduction over extended sections , e.g., C(7) and C(9) through berm formation. Semi-stabilised with vegetation. Vulnerability to 'flushing' at higher flows ?	Moderate - High (5-8): Banks relatively cohesive clays. Flow variability . Riparian diversity.	Stabilisation of berms, possible use of groins to maintain low flow width.

REACH SUMMARY INFORMATION - THE BOURNE

Reach location	Site/s	PDP / Response	Channel stability	Channel sensitivity	Opportunities for enhancement
Woburn Bridge	B(1)	Possibly over-widened / re-sectioned in U/S reach to Wey: Minimal response, low energy stream.	High: Minimal adjustment observed. Minor toe sedimentation.	Moderate: (4-5): Diversity increased in wooded section.	
Corrie Road	B(2)	Channelised/culverted: No adjustment observed.	High: Adjacent naturalised banks	Low (1)	Minimal opportunities short of major structural change to channelisation.
Crockford Road	B(3)	Re-sectioned ?: Channel appears over-widened. Minimal morphological response.	Moderate - High: Evidence for bank erosion, but clayey banks, whilst vertical in places remain generally stable.	Moderate: (4-6): Reasonable diversity to banks.	Provision of vegetative buffer alongside footpath L/B.
Chertsey Road	B(4)	None identified: Channel remains in naturalised condition through woodland.	Moderate: Channel incision, clays promote steep vertical bank faces before failure, stabilisation with trees. Sediment assemblages within channel.	High: (8-9): High diversity of form, naturalised channel.	'Do nothing' option favoured. Minimal heavy maintenance advocated.
Mill Bourne (Emmetts mill)	B(5)	Mill: Minimal adjustment to D/S reach. minor sedimentation at bank toe.	Moderate- High: Channel demonstrates minimal adjustment to imposed conditions. Clayey banks stable. Possible some vertical incision immediately D/S from mill.	Moderate High (5-7): Cohesive sediments make channel less sensitive to adjustment.	Minimal heavy maintenance.
Chobham	B(6)	Partially channelised / re-sectioned: Minimal adjustment.	High: Channel appears in equilibrium with imposed conditions. No obvious evidence for erosion. minor fines at bank toe.	Moderate (4-6): Semi-naturalised form despite adjustment.	Enhancement of flow diversity - width reduction?

REACH SUMMARY INFORMATION - HOE STREAM

Reach location	Site/s	PDP / Response	Channel stability	Channel sensitivity	Opportunities for enhancement
Old Woking	H(1)	Weir: Channel over-widened.	Moderate - High: Minimal contemporary adjustment observed. Evidence for past lateral change.	Moderate (4-6): Bank diversity. Minimal bed form.	
Wych Hill (Woking)	H(2)	Localised bank protection: Sediment input to channel, transport through reach.	Moderate: Local instability, e.g., H(2), otherwise banks fairly cohesive.	Moderate (5-6): Disturbance locally where channel backs residential property.	Bank protection / localised bank regrading and stabilisation.
D/S Mayford bridge	H(3)-H(4)	Minimal (possible local re-sectioning).	High: Scant evidence for bank failure or for sediment accumulation. Banks cohesive and stable.	Moderate - High (6-7): Wide diversity of form. Bed variability.	
Kemmishford bridge - Rickford mill	H(6)-H(7)	Mill/weir: Channel adjusted to imposed conditions.	Moderate: Local instability, e.g., bank slumping H(6) where open pasture. Bed stability, armour layer provided by course fraction in clay matrix.	Moderate (5): Moderate diversity , lacks riparian vegetation in some sections of reach.	Enhancement of riparian vegetation cover to bank. Restriction of access to channel, provision of buffer.
Whitmore Common Brook	H(5)	Semi-channelised: Channel adjusted to imposed conditions.	High: Banks steep, but stabilised through bankside vegetation where unprotected. Bed stable, little evidence for deposition.	Moderate (4-5): Sensitivity lowered where banks protected locally.	Removal of protection measures - regrading of banks and restoration of more naturalised cross-section.
Wood Street Brook	H(8)	None identified: Channel incised within clays.	Moderate - High: Clays allow incision whilst maintaining bank stability. sedimentation at bank toe. These could possibly be flushed through at higher flows.	Moderate - High(6-8): naturalised channel, lacks some bed diversity through fine deposition	Stabilisation of fines at bank toe?
Clasford Brook	H(9)	None identified: Naturalised condition, accumulation of CWD within channel	High: Banks cohesive and stabilised with vegetation. Bed semi-armoured with fine gravel's in sandy-clay matrix.	Moderate - High (6-8): Naturalised channel, high morphological diversity.	Periodic light maintenance to observe obstruction through CWD and morphological impact.

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