This work is dedicated to
the memory of
Sydney Howard Tabb
1906 to 1995.

The contents of this thesis are original
and all the work was carried out by the
author - the results presented herein
are not taken from any other thesis
by the author.

Signed...S. T. Winterbottom...

An analysis of channel change on the Rivers Tay and Tummel, Scotland, using GIS and remote sensing techniques.

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Volume One: Text

Abstract

This thesis examines historical river channel change on a 12km study reach of the Rivers Tay and Tummel Scotland via the development of GIS and remote sensing techniques. Firstly, historical maps were combined using GIS rectification techniques in order to examine channel changes over the period 1755 to 1975. Secondly, also using GIS methodology, channel planforms as depicted in a series of aerial photographs were overlain to study recent channel change (1971 to 1994) including that caused by two major flood events. The study formed part of wider investigations into the hydrology and geomorphology of the River Tay, following the 1990 and 1993 flood events commissioned by organisations involved with management of the river.

The study reach in 1863 and 1899 was shown to have alternating, highly divided sections with multiple mid-channel islands, and stable single-thread sections although, overall, the channel was less braided than depicted on 18th century maps. By 1975, the multi-channel sections had changed to a predominantly single-thread character and it is proposed that this had occurred in response to flood embankment construction and bank protection leading to channel narrowing and incision. This has wider implications for the management of the River Tay as channel instability supports diverse natural habitats with high conservation value.

Once recent river planform changes on the study reach had been identified, stable and unstable reaches were defined allowing the determination of the degree and nature of instability using GIS methodology which included quantification of active channel widths and gravel area, braiding indices, sinuosity and channel occupancy indices. A number of unstable reaches were also studied in the field to examine the processes responsible for river bank erosion. In addition, the effect of in-channel morphology on river planform changes was examined by applying image analysis to bands 3, 5, 6 and 8 of airborne multi-spectral imagery (Daedalus ATM) to map channel bathymetry.

The results showed that changes in channel planform and position occurred almost entirely in response to extreme flood events and that areas of greatest channel change were in zones of historical instability resulting from the presence of less cohesive sediments along the courses of former river channels. A meander-like alternation of pool-riffle sequences controlled the local distribution of bank erosion along most of these reaches by deflecting thalwegs against outer banks.

The information derived from the study was used to construct an erosion hazard map. Using raster-based GIS techniques, these data were combined with measurements of distance from river channel and flood return periods, to create a model which enabled spatial mapping of river bank erosion probabilities. These probabilities were then mapped for hypothetical floods of 5, 10 and 25 year recurrence interval.

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CHAPTER 1

INTRODUCTION

"*What wonderful river-lore the Tay must have whispered during the long ages of its existence to the scenes which it nourished; lore of nature's changes and human conflicts, of lost landscapes and lost peoples over whom it has long rolled the deep tide of oblivion*" (Macmillan 1901).

1.1. Introduction

The population explosion over the last hundred years has brought humans into conflict with their environment and nowhere has this become more evident than on the world's floodplains. Major flood events, with associated property damage and the loss of fertile land through river bank erosion and floodplain scour, have often been the focus of this conflict. The human aim to understand and attempt to control nature, has brought about a wealth of studies of the fluvial system and, as floodplain land-use becomes a more critical issue, the natural wandering tendencies of rivers has come under closer scrutiny.

In the past, river channel changes have inspired the interest of many and produced a wealth of quality research and literature as a result. However, the technological advances that have come about over the last ten to fifteen years have provided extended opportunities to study channel change in greater detail and on wider spatial and temporal scales.

Geomorphologists must be quick to embrace new technology and explore the possibilities it offers. This research is part of the beginning of that exploration.

Wherever possible throughout this study, new methods for examining the various aspects of channel change have been developed to use new technology to its best advantage. The study of morphological change is important for gaining an understanding of our environment and the primary aim of the project was to determine the nature and causes of channel change within the Tay river system. However, the study of morphological change is also a fundamental requirement for floodplain management decision making and so the emphasis of this project has been on the practical application of new techniques to establish the benefits and possibilities that they provide in this respect. A small case study area was employed to identify and analyse channel changes and to test the methodology developed. The wider applicability of the techniques is discussed.

1.2. The River Tay

The River Tay (figure 1.1. see Volume 2.) in terms of discharge is Britain's biggest water course. It has a mean annual discharge of $160m^3s^{-1}$ and a catchment area of $4690km^2$. From its headwaters draining much of the Grampian mountains, to the wide mud flats of the estuary at Dundee, the catchment area of the Tay encompasses mountain torrents, vast serene lochs and mighty wandering rivers. Throughout history, the River Tay has played an important role in the human development of this area. It provides transport; it provides fertile land by laying rich alluvium on the valley floor during its floods; it provides an important corridor through the hilly landscape upon which people have been able to travel and develop; and it also provides a beautiful landscape which has, and still is, important for recreation and tourism. It is a celebrated and integral part of the landscape and lives of the people. This is clearly demonstrated by the wealth of romantic literature and art it has inspired.

The peoples relationship with this river has not always been an easy one however. From time to time extreme weather conditions turn this landscape feature into a terrible force of nature. Many historical sources give accounts of mighty floods tearing away bridges, flooding houses and taking the lives of those unfortunate enough to get in its way. This conflict is one which the people living on the floodplains of the Tay and its tributaries, have so recently been reminded.

1.3. Study background

February 1990 saw widespread flooding on the Tay; the first major flood since 1951. This followed what is now recognised as 40 years of particularly dry weather in the Tay's history (Smith and Bennett, 1994) and so the extent of the flooding was surprising to many and devastating in consequence given the amount of floodplain development which had taken place in the previous decades.

Inundation occurred over 34km^2 of the Tay floodplain. In the Tay catchment 42km of floodbanks were overtopped and embankments were breached at 46 locations (Babtie, Shaw and Morton, 1990). Damage was assessed to be in excess of £3.2 million with the cost of repairs in agricultural areas accounting for 34% of this sum. Most of this money was expended on the repair of embankments and damage directly attributable to their breaching. Another 29% of the costs were due to disruption of road and rail communications (Babtie, Shaw and Morton, 1990).

A simple desk study of flood damage and embankment breaching undertaken in 1990 by Gilvear and Winterbottom (1992), suggested that zones exhibiting historical instability are the most susceptible to channel change and embankment breaching during flood events. This was borne out by archive sources which described embankment failures, and road and railway damage, at many of the same locations which were affected during the 1990 flood. This research highlighted the need for further investigation of historical channel instability and the affects of old river channels on present day river channel change. As a result, this project was funded by Tayside Regional Council, The Scottish Office and Perth and Kinross District Council, with the aim of identifying the causes and effects of river channel change on the Tay.

The first problem in a study of the River Tay is its size. The majority of research on British rivers is carried out on small rivers and streams, with little work on anything of comparable size to the Tay. This meant that the tried and tested techniques and methods for studying river channel change in the UK were inappropriate for this project. For example, the rate of bank erosion is often studied with the use of erosion pins (Wolman, 1959; Twidale, 1964; Hill, 1973; Hooke, 1980). Bank erosion during an extreme flood event on the River Tay, was observed to be in the order of 10 metres on some reaches so another method of measurement was needed. The shapes of river cross-sections have been shown to have significance with respect to river channel change (eg. Knighton, 1977), but clearly in a river with widths between 60 and 120 metres and water flowing at high velocities, the usual method of taking cross-sections by traditional surveying techniques is not feasible. Additionally, without great resources this method is only suitable for the study of small isolated reaches of rivers which often leaves the questions regarding down and upstream influence unanswered. Consequently, a major part of the study was devoted to the development of new and appropriate techniques for geomorphological investigations into more sizeable rivers.

1.4. Study area selection

It was decided that a study reach (10 to 20km) was needed on which to test methods developed. A length of the River Tummel from Pitlochry to its confluence with the Tay, and the Tay from there to just above Dunkeld was chosen (figure 1.1). This area is predominantly agricultural and suffered major damage during the 1990 flood. Gilvear and Winterbottom (1992) identified this reach as showing historical instability. Small stable reaches are interspersed with unstable, wandering gravel-bed reaches. The River Tummel component of the study area is now relatively unrestricted in its wanderings as most of the 19th century embankments have been allowed to fall into disrepair. Embankments on the River Tay part of the reach are still maintained and have confined most of the channel to stable single-thread reaches and this allows two contrasting areas to be examined.

The study was limited to this area for the duration of the project and several aerial surveys of this reach were carried out by NERC over the three year period. This provided an extremely valuable data set which would not have been available for a larger area.

1.5. Aims and Objectives

The overall aim of the project was to ascertain the nature and causes of channel change within the Tay river system in order to aid floodplain management decisions. This would lead to the production of a floodplain erosion hazard map that identified areas vulnerable to change and those most susceptible to the effects of flood events. In addition, the ability to predict areas of change and model future scenarios was thought to be useful. In order to speculate on the future however, it is necessary to examine the past and present which provides a better basis for predicting future channel change (Hooke and Redmond, 1989).

As previously mentioned, traditional techniques in Britain for studying rivers were mainly developed for small rivers and streams. It was therefore a necessary and integral part of the study to develop and appraise new techniques appropriate for a river of this size. These methods were based on GIS and remote sensing techniques with field validation of the results. As well as the overall aim, there were also several specific objectives which are outlined below.

1.5.1. Specific objectives

1. To develop the use of GIS techniques for the study of channel change on relatively sizeable rivers and to assess the usefulness of these methods.

2. To examine the use of remotely sensed data (both aerial photography and ATM data) for identifying 2 and 3-dimensional channel change.

3. To quantify rates and types of channel change that have occurred within the study reach both on a short and long-term basis.

4. To determine the principal controls on channel instability within the study reach.

5. To produce a predictive model of channel change for the study reach.

1.6. Structure of thesis

The numerous diagrams and maps that resulted from this research are contained in a separate volume (Volume 2.) and should be read in conjunction with this volume (Volume 1.) which contains the text.

The thesis is in five parts. The first part, comprising chapter 2 is a literature review examining published research relating to river channel change (principally within the United

Kingdom) focusing on the factors that affect the rate and distribution of river channel change and techniques for assessing them. A review of research based on rivers in Scotland is presented followed by an examination of studies specific to the River Tay system.

The second part of the thesis, encompassing chapters 3 and 4, involves the identification and quantification of river channel changes within the study reach. Chapter 3 involves a GIS study of available maps of the area and identifies the historically unstable sections of the river. Remote sensing methods are used in a study of floodplain sediments to examine changes over a broader time-scale. The chapter then details the history of the study area and significant flood events as determined from archive sources. In addition, an investigation of rainfall trends places the historical changes into perspective with present day conditions.

Chapter 4 involves a closer examination of channel change over a more recent time-scale using GIS software to rectify and overlay aerial photographs. The study also incorporates a comparison of data derived from field survey. The channel changes identified are related to the river flow regime via an examination of discharge records. An examination of embankment breaching and damage caused by the 1990 and 1993 floods, is also presented.

Part three of the thesis (chapters 5 and 6) examines the relative importance of the various factors influencing rates and distribution of river channel change. Chapter 5 explores the use of image analysis on airborne thematic mapper data and aerial photographs for investigating in-channel morphology and its affect on river planform.

Chapter 6, which is divided into two main sections, investigates other causative variables affecting channel change and the quantification of their importance. The first section deals with variables identified by field investigation including bank sediments, height of banks, slope of banks and channel slope. The second section assesses the use of remote sensing for the classification of riparian habitats. Vegetation composition and distribution are examined and the relation of these to fluvial surfaces is attempted.

The fourth part of the thesis, presented in chapter 7, involves the development of a raster-based GIS model which allows erosion probabilities to be mapped. The model uses the information derived from the studies presented in the previous chapters.

The final part, Chapter 8, concludes the thesis with a review of the research aims and discusses the achievement of these aims. The wider applicability of the techniques developed throughout the thesis are considered along with the geomorphological implications of the Tay study for other Scottish rivers. Finally, recommendations for further work are proposed.

CHAPTER 2

LITERATURE REVIEW

2.1. Introduction

The study of river channel change has become a prominent feature in fluvial geomorphological studies (eg. Gregory, 1977; Ferguson and Werritty, 1983; Hickin, 1983; McEwen, 1989) and an abundance of literature has arisen from such investigations. Hickin (1983) has defined the study of river channel changes in the narrowest sense as, "the collection of empirical and theoretical studies concerned with the adjustment of channel cross-sectional size, form and pattern shifts in environmental conditions" (page 63). This review will outline the main criteria used in studies of channel change which are illustrated, where possible, with examples of work carried out in Britain. Firstly, definitions of some of the terms used in this study, will be outlined (section 2.2.) after which the adjustable elements of a river system are defined (section 2.3.) followed by a explanation of the timescales used in this study (section 2.4.). In section 2.5. the nature of river channel change is discussed followed by a review of the causes of channel change and the factors which affect its rate and distribution (section 2.6.). Floodplain formation is discussed in section 2.7. and an overview of techniques used to assess channel change is presented in section 2.8. Finally, a review of studies carried out in Scotland (section 2.9.) and on the River Tay (section 2.10.) are given.

2.2. Definitions

It is necessary at this point in the thesis, that some of the terms central to this study, are defined; namely that of flood, floodplain and associated features, channel reach and channel section. The most usual definition of a flood is that of an overbank flow. However, the term "flood" used in this study, is defined in terms of geomorphological significance in that it is channel disruptive, rather than channel forming. Channel forming events are those which shape the form of the river in its equilibrium state, whereas channel disrupting events are those which cause a departure from the natural state of equilibrium. The size of a flood with this definition will vary both within and between rivers. For example, McEwen (1989), in a study of the River Dee, describes an extreme event which had a disruptive effect as having a recurrence interval in excess of 100 years with moderate discharges responsible for returning the channel to an equilibrium state as having a 10-50 year recurrence interval. Within the study reach used, for example, a major flood event in January, 1990, occurred which was calculated as having a 25 year recurrence interval for the River Tummel (TRPB, 1993). This flood had a large disruptive impact on the channel and surrounding floodplain. The definition of a geomorphologically significant flood in relation to this study, is one with a recurrence interval of between 15 and 20 years. Smaller flood flows will be termed moderate events.

A simplified definition of a floodplain is given by Bren (1993) who describes a floodplain as a relatively level area of sediment deposited, and periodically inundated by rivers. In this study, a further distinction is made by use of the term "active floodplain", which includes the area enclosing all parts of the floodplain which show evidence of having been worked by the river at some time, and therefore, consists of sediments deposited within an active channel rather than solely by overbank flow.

Several floodplain features are referred to in the text which also require definition. The first of these is "old channels" which refers to all areas of the floodplain reworked directly by fluvial activity and consisting of within-channel sediments. Secondly, the term "former channel" is used to denote historical channels identified from maps dating back to 1755. Lastly, the term "abandoned channel", relates to "former" or "old" channels, which have been abandoned leaving behind a complete linear feature on the floodplain.

There are also two main locational terms which are used in this study and require clarification. The term "reach" used in this thesis refers to an undefined length of river which tends to exhibit fairly uniform characteristics. The exception to this however, is the term "study reach" which is used to define the total length (12.5km) of river examined in this thesis. The term "section", refers to lengths of river that are specifically designated in chapter 3 and are numbered for identification.

2.3. Adjustable elements of the fluvial system

In a study of channel change it is important to establish which factors of the river channel form are free to adjust and in doing so constitute a channel change. Hey (1978) proposed that a river has 7 degrees of freedom in that it may change its velocity, hydraulic radius, slope, wetted perimeter, maximum flow depth, sinuosity and meander arc length in response to changing independent variables. A simplified version is proposed which encompasses all these variables within 4 degrees of freedom:

> slope, velocity, hydraulic geometry (channel cross-section) and channel planform parameters (width, sinuosity, braiding index and pattern).

Therefore, in any investigation of river channel changes these are the morphological and hydraulic variables which must be studied in order to establish any quantitative or qualitative assessments of change.

2.4. Time-scales of river channel change

The second factor, which must be considered in studies of environmental change, is the timescale over which they may occur. Richards (1982) identifies three time-scales of change:

- Long-term: influenced by climatic, hydrologic and gradual tectonic effects.
- Medium-term: 'forced' by human activity creating a temporary disequilibrium in the channel.
- Short-term: individual, random and extreme events causing catastrophic changes.

Hickin (1983) has a slightly different definition:

- Geologic: thousands to millions of years,
- Geomorphic: hundreds to thousands of years,
- Engineering: tens of years.

However, in both the above definitions there are gaps between the time-scales. In this study the terms geologic, geomorphic and engineering time will be used with the following definitions:

- Geologic: changes which took place several hundred to thousands of years ago influenced by climate and tectonic effects.
- Geomorphic: relating to changes of over fifty years to those of several hundreds of years. These changes include those in response to climate and hydrologic regime change as well as those caused by human activity.
- Engineering: relating to recent changes that have taken place over the last fifty years caused by individual or sequences of flood events or human activity.

2.5. The nature of river channel changes

The third factor which must be established is what actually constitutes a channel change and the nature of changes taking place. This is much more complex in its definition. There is a great deal of discussion in the literature on the concept of equilibrium (eg, Leopold and Maddock, 1953; Schumm and Lichty, 1965; Ferguson, 1977; Harvey et al., 1979). Hickin (1983) proposes that an undisturbed river will establish a stable combination of morphological elements and this state is defined as being in equilibrium. This theory is furthered by the concept of regime theory (Inglis, 1949) which assumes a dynamic equilibrium (Lewin, et al., 1988) whereby a channel is adjusted to its discharge regime and although processes of erosion and deposition continue, the overall form is preserved to produce a dynamically stable pattern. The difficulty lies therefore, in establishing whether observed movements are part of natural morphological adjustment within a state of dynamic equilibrium, or whether a channel metamorphosis is taking place (Schumm, 1973).

Two major types of channel planform alteration can be identified. The first is migratory change which usually takes place gradually through the processes of erosion and deposition. This type of change is usually associated with meandering rivers. Hooke (1977) examined changing meander patterns on the Rivers Axe and Culm in Devon and identified two types of related channel movement. The first occurred where the channel had translated downstream but had maintained its planform dimensions. This type of channel migration can be considered as a natural process occurring within a system of dynamic equilibrium and therefore, in the strictest sense, does not constitute a channel change. The second type of movement identified can be regarded as true channel change and constitutes an alteration in channel parameters and form (hydraulic geometry, sinuosity, braiding index and pattern). Change of channel form is evident in measurements of channel sinuosity which Hooke and Redmond (1992) state is a major indicator of channel response. An increase in peak discharges is expected to decrease sinuosity via an increase in meander wavelength and therefore causing channel straightening. Conversely, decreases in discharge would be expected to increase sinuosity (Hooke and Redmond, 1992). Another type of true change is that of pattern character which may be defined as the transition from a channel exhibiting characteristics of one type of pattern to those of another. Three major types of river channel pattern have been defined in the classic paper by Leopold and Wolman (1957). The three channel patterns discussed are straight, meandering and braided although these are not seen as separate entities but as extremes in an uninterrupted range of channel pattern. Kellerhals et al. (1976) described a whole continuum of channel forms which occur in response to changes in sediment supply and channel slope (figure 2.1). Many studies of channel change focus on the transitions between these states.

It is evident from studies of upland British rivers, that one of the first problems usually encountered is the classification of river planform which often displays an intermediate state. Ferguson and Werritty (1983) working on the River Feshie, Scotland, make the following observation:

> *"Many actively changing pebbly rivers have moderately divided channels of low to medium sinuosity which combine features of both meandering and braiding. Such rivers have generally wide shallow channels, flanked and locally divided by expanses of bare gravel, but lack the degree of channel division characteristic of archetypal pro-glacial braided rivers. They have a well defined pool-riffle sequence with a meander-like alternation of riffle orientation, but erosional banks are not always or exclusively found on the outside of meander bends and channel sinuosity is lower than in freely meandering rivers.* (page 181)

This class has been defined separately as "a wandering gravel-bed river" (Church et al., 1981). This particular classification is an appropriate one to use for the study reach examined in this thesis. These river types lie on the meandering/braided threshold and channel change tends to occur by a movement towards meandering or braiding characteristics.

Leopold and Wolman (1957) introduced the concept of planform change occurring in response to the crossing of significant thresholds. Many definitions of thresholds exist, but perhaps the most concise is that of McKerchar (1980) who defines a threshold as "the point at which a stimulus begins to produce a response". However, much debate has arisen out of this topic mainly involving the actual existence of thresholds and also of their nature particularly in relation to channel pattern (eg. Ferguson, 1977; Hooke and Redmond 1992; Newson, 1992).

Leopold and Wolman (1957) first identified the meandering/braiding threshold when they plotted different rivers as points on a graph of channel slope against bankfull discharge. It was found that a line could be drawn separating meandering and braided channels defined by the equation $s=0.013Q^{-0.44}$ (s=slope, Q=discharge). Meandering channels plotted below this line and braided ones above. Straight channels plotted arbitrarily above and below. Many refinements and redefinition's of this equation have been produced, several of which use values to incorporate influences of bed and bank material (Henderson, 1961; Parker, 1976; Ferguson, 1984) but it is thought that the transition between these two states involves the crossing of a threshold of some sort but whether this is a gradual or a rapid transition is also the subject of much debate (eg. Chappell, 1983; Hooke and Redmond, 1989).

The theme of gradual transitions and abrupt change is extended by Graf (1979; 1988) who introduced the mathematical concept of catastrophe theory into the realms of fluvial geomorphology. Catastrophe theory assumes that a system is in equilibrium with mutual adjustment of the system elements. In its simplest form, the cusp catastrophe, the system is defined by two independent (a,b) variables and one dependent variable (x). When the system is in equilibrium, the values of a, b and x plot on a three-dimensional surface (figure 2.2a.) as defined by Thom (1975). This conceptual surface has a fold where values of x may have one of two equilibrium states. Graf uses as an example, bank resistance and stream power as the two independent variables and sinuosity as the dependent variable. Figure 2.2a. shows how changes in the independent variables can result in different types of transition from a meandering planform pattern to a braided one. In figure 2.2b. and 2.2c. the transition occurs rapidly due to a sharp increase in stream power such as would occur during a flood event. Recovery and reversion to a meandering system may take place either abruptly (back over the catastrophe cusp as in figure 2.2b.) whereby the stream power rapidly decreases and bank resistance remains at its initial level, or more slowly if the bank resistance has been lowered as a result of the event (figure 2.2c.). Figure 2.2d. shows how a stream with an intermediate condition can become either meandering or braided depending on changes in stream power and/or bank resistance. This clearly relates to observations by Ferguson and Werritty (1983) who suggest an initial common stage of pool-riffle sequences from which channel pattern may develop as braided or meandering determined by stream power in relation to bed and bank erodability. The development of a meandering channel requires bank erosion to be localised at the point of maximum current attack opposite riffles so that sinuosity increases and bars become anchored on the inside of bends. The development of braided patterns from the initial stage, requires a more general widening of the channel (Leopold and Wolman, 1957) and therefore indiscriminate erosion as would be expected with much higher stream power.

It is clear then, that in dealing with rivers which have a transitional planform that a change of state between channels of meandering and braiding tendencies is an important concept in studies of channel change and represents the crossing (either by gradual or rapid means) of a threshold. Chappell (1983) makes the further distinction of thresholds as either transient if the effect is temporary or intransient if it is permanent.

Apart from studies of channel planform changes, much research of British rivers has involved changes in the vertical dimension (Newson and Macklin; 1990, Macklin et al., 1992, Rumsby and Macklin; 1994). This has not been studied in relation to the field area chosen for this thesis, so is not relevant to this discussion except to note the existence of such processes.

In summary of this section three main points can be made:

1. If a channel is actively eroding and depositing causing movement across the floodplain but there is a preservation of channel parameters and form, this does not constitute a channel change but is a state of dynamic equilibrium.
2. Channel change is indicated by changes in width, sinuosity, meander arc length, braiding index or by a transition between meandering and braided patterns.
3. Channel change may be either gradual or rapid marked by the transgression of a significant threshold, i.e. channel metamorphosis.

2.6. Causes of channel change and factors affecting its rates and distribution

Figure 2.3. shows how the processes of erosion, aggradation and avulsion leading to channel change, are the result of a complex interaction between the numerous elements which constitute a fluvial system. In the past, variables that influence adjustments of river channels, have been considered as either intrinsic or extrinsic (Lewin et al., 1988). However, with the possible exception of climate, none of the variables could be considered as being wholly intrinsic or wholly extrinsic due to their dependence on, and/or interaction

with, other variables within the system. Neither, for the same reason, is it possible to isolate the effects of any one individual element. However, certain generalisations can be made about these system elements and a brief review of these follows.

2.6.1. Climate

The effects of climate change are probably the most important factors controlling river regime and, therefore, river channel changes. Rumsby and Macklin (1994) made a detailed study on channel sections within the Tyne Basin. Research focused on vertical channel changes in response to climatic fluctuations. Channel trenching and incision coincided with a predominance of higher meridional circulation (north/south winds caused by an increased temperature gradient between the equator and the poles) which brought about a higher frequency of major floods. Zonal periods (predominance of west to east winds) coincided with a higher frequency of moderate floods in the Tyne Basin probably because the Tyne is in the eastern rain shadow of the Peninnes. This resulted in accelerated bank erosion and lateral reworking in the upper Tyne releasing sediment which caused exceptionally high within-channel deposition in the middle and lower reaches. Intermediate periods, identified as having relatively equal amounts of meridional and zonal weather conditions, were characterised by low flood frequency and channel stability (Rumsby and Macklin, 1994).

Rumsby and Macklin (1994) give dates for historical, predominant weather conditions as follows:

High meridional circulation - 1875-1894, 1955-1969

High zonal circulation - 1861-1874, 1919-1954

Intermediate - 1895-1919, 1970- 1979

Recently, an increase in major floods within the Tyne basin, has resulted in bank erosion and channel widening (Rumsby and Macklin, 1994). This has corresponded with low frequencies of meridional and zonal weather but an increase in non-directional synoptic (pure cyclonic and anticyclonic) weather systems (Briffa et al., 1990).

Studies by McEwen (1986, 1989) have examined river channel changes in response to climatic fluctuations over the last 200 years and note that an increase in moderate to extreme flooding in the late 19th Century coincided with the latter stages of the little ice age which provided a significant snowmelt contribution to flooding.

Based on observations of streams in North West England, Harvey et al. (1979) found that abnormally dry weather and lack of large rainfall events in the early 1970s, resulted in streams remaining in a stable dynamic equilibrium with no major thresholds approached.

2.6.2. Discharge

There has been a great deal of debate on the effects of varying river discharges on river channel form. Most of the discussion centres on the magnitudes and frequency of flood events and a review of some of this work follows in this section.

Much research has been carried out on the effects of large flood events and subsequent recovery from those events (eg. Werritty, 1984; Thompson, 1987; McEwen and Werritty, 1988). Lewin (1989) notes that some floodplains are "catastrophe related" in that their morphology is best interpreted as a response to, and a recovery from, rare events. Werritty and Ferguson (1980) observe that on the River Feshie, high magnitude events obliterate former channel patterns replacing them with chaotic and unstable braiding patterns. Subsequent reworking by lesser flows simplifies the channel to a single sinuous channel which divides around medial bars. Therefore, the channel pattern is conditioned by the last flood and the length of recovery time. Similar findings are reported by Lewin et al. (1988) in a study of the River Tywi which is described as having a transitional pattern. Here, floods generate major lobate, gravel-bed forms with avalanche faces and a multichannel system. Between floods a reversion takes places to a meandering channel with bars becoming islands or attached to one side or another. McEwen (1989) noted that an extreme event of long recurrence interval (in excess of 100 years) will have a major disruptive impact providing that room is available for expansion of the active channel area and that thresholds for disruption are surpassed. Post-flood moderate discharges (10-50 years recurrence interval) are more important in returning the channel to quasi-equilibrium form than disrupting it (McEwen 1989). Thompson (1987) working on the Langdon Brook in the Bowland Fells, deduces that the precise configuration of a stream should reflect the most recent discharge events.

Many researchers note, however, that individual floods cannot be taken out of context and it is the magnitude and frequency of all events that is important in shaping the fluvial landscape. Much work has focused on the concept of dominant discharge identified as that which is most responsible for the formation of observed channel pattern (eg. Ackers and Charlton, 1970; Harvey, 1975; Richards, 1982). There is a great deal of dispute as to what defines the dominant discharge and in reality, it probably varies from river to river, and time to time. Dury (1961, 1976) relates channel dimensions to flood events of 1.58 years return interval, while Hitchcock (1977) quotes a return interval of 1 year as being most important in forming channel pattern. Most authors however, give a figure of between 1 and 2 years recurrence interval as being the dominant discharge (eg. Leopold et al., 1964; Lewin and Hughes, 1976). If this is the case it can be seen that changes in flood magnitude and frequency could have a large impact. However if, as much evidence suggests, channel form is influenced most by recent extreme flood events and relates to flood response and recovery, the effects of magnitude and frequency of events are still important.

Carling and Beven (1989) state that the effects of one flood can be different from a similar previous flood if the relaxation time of the first flood is longer than the time elapsed before the occurrence of the second flood. After major thresholds have been exceeded there is a period of lesser response to events of high magnitude until intrinsic thresholds are restabilised (Wolman and Gerson 1978). Harvey et al. (1979) note that changes in relative flood frequency could influence the stability of the system, with a decrease in stability being brought about by the lowering of an upper threshold as a result of the cumulative effects of a number of moderate events. An increase in stability may result from vegetation colonisation associated with moderate events and with long periods between major events.

However, the effects of varying discharges and individual events may vary from reach to reach within a river system and each will have different thresholds and responses. Research into the effects of a high magnitude event on the Clunie Water by McEwen (1989), showed that lower slopes and restricted sediment supply meant a relatively stable pattern was maintained. The Quoich and Lui, waters with steeper slopes and greater sediment supply however, showed evidence of major disruption.

In reality, it is difficult to make generalisations about the effects of river discharge. It is likely that the effects of varying discharges will differ between rivers and also between reaches within rivers. It is therefore important in a study of river geomorphology, to determine the response of each river and its individual reaches, to its own particular discharge regime.

2.6.3. Bank Stability

The effects of bank stability can be very important to studies of river channel change (eg. Thorne and Lewin, 1979; Hooke, 1980; Hooke and Redmond, 1992) as they can have a major affect on rates and distributions of change. There are three main controls on bank stability; bank sediments, bank slope and height, and vegetation.

Bank sediments are probably most important in determining bank stability and can be divided into three categories; cohesive, non-cohesive and composite. Cohesive sediments are generally regarded as the most stable of the three types with erosion taking place by the detachment and entrainment of aggregates or crumbs of soil. Resisting forces are the result of cohesive bonds between the particles (Thorne, 1982; Lawler, 1993) which in turn are a function of mean particle size, clay and organic matter content, type of clay and bulk density or void ratio (Grissinger, 1982). Banks with highly cohesive material often fail as blocks. This frequently occurs after, rather than during high river flows (Hooke, 1979) due to the excess weight of the sediment when it has been saturated (Thorne, 1982). Non-cohesive sediments are generally much more erodable. Erosion takes place by entrainment of individual grains and resistance depends on the intergranular forces due to interlocking, especially in imbricated sediments (Thorne, 1982). Composite or stratified banks, consist of layers of cohesive and non-cohesive sediments. These are subject to a combination of erosion processes. Generally, the non-cohesive sediments are eroded more rapidly, and where these underlie the cohesive sediments this leads to overhanging and the eventual mechanical failure of blocks of the overlying cohesive sediments (Thorne and Tovey, 1980).

Bank slope and height also have important implications with regard to bank stability. The lower the angle of the bank, the more stable it will be. Oversteepening of banks generally leads to instability and mechanical failure (Thorne, 1982). In a study by Twidale (1964) it was found that the fastest retreat occurred on the steepest banks being monitored. Generally, lower banks are more stable than high ones.

Bank erosion usually occurs due to the undercutting of banks by fluvial action followed by mass failure. Thorne (1990) points out that vegetation can significantly affect both flow erosion and mass stability. Dense vegetation on a river bank can increase its erosion resistance by one or two orders of magnitude (Carson and Kirkby, 1972; Kirkby and Morgan, 1980). Nevins (1969) for example, working on braided channels in New Zealand, observed that planting of Salix spp. shrubs on river bends produced a change from braided to a single thread planform due to an increase in bank stability. Brice (1964), Kondolf and Curry (1986) and Bray (1987) noticed a switch in pattern from meandering to braided as a result of vegetation removal. Vegetation provides direct protection to the soil and the roots bind the soil to increase cohesion. Vegetated banks are also much drier and better drained further reducing erosion risk (Thorne, 1990). Vegetation must extend down to the average low water level to be effective otherwise the roots may be undercut. Therefore, plants tolerant of inundation are most effective. With trees for example, if the bank height exceeds the rooting depth and undercutting occurs, trees will begin to drag the bank down due to higher bank angles with greater weight at the top that produces both a shear force and a turning moment that causes toppling failure (Thorne, 1990).

2.6.4. Stream Power

Stream power, which can be defined as the rate of energy supply at the channel bed, has important effects on erosion, sediment transport and aggradation which are three of the most important factors in shaping the fluvial environment (Bagnold, 1966). Stream power per unit channel (Ωwatts per metre) length can be defined as:

$$\Omega=\rho g Q s_e \qquad (2.1)$$

where ρ=density of water, g=gravity, Q=discharge and s_e=channel slope. Specific stream power (ω), which is energy available for unit of bed area is defined as;

$$\omega=\Omega/W \qquad (2.2)$$

where W=width of channel (Bagnold, 1977). As the values of ρ and g remain constant, it can be seen that stream power is highly dependent on channel slope and discharge.

Specific stream power determines the rate of sediment transport and can directly affect bank stability by sediment removal and transport from the basal area of river banks in what Carson and Kirkby (1972) termed "basal endpoint control". Thorne (1982) has outlined three states of basal endpoint control which depend on the balance of supply and removal of material:

1) Impeded removal - bank failure supplies material to the base at a higher rate than it can be removed by fluvial entrainment. This results in basal accumulation and a decrease in bank angle and height and therefore increased stability.

2) Unimpeded removal - sediment supply rates from bank failure are equal to rates removal of sediment by fluvial action. No change in bank profile occurs.

3) Excess basal capacity - sediment removal from base of bank exceeds supply by bank failure. This results in basal scour increasing bank angle and height and thereby inducing a greater instability.

2.6.5. Sediment Transport

There are three main ways in which rivers can transport sediment; in solution, in suspension and along the river bed (bedload). Solute transport involves the movement of soluble salts dissolved in the river water but is not relevant to this study and will not be discussed here. Suspended sediment transport involves the movement of small particles held by the vertical velocity component of turbulent fluid eddies (Richards, 1982). This process is important for the removal of small particles supplied to the river by bank erosion as discussed in section

2.6.4. as well as transporting sediment washed into the river by processes of overland erosion.

The most important type of sediment transport in terms of this study however, is that of bedload transport. Bedload transport is directly dependent on specific stream power and sediment size and requires the exceedence of a threshold of flow intensity in order to overcome the resistance to movement of bedload particles. The resistance is determined by particle size and shape and is also dependent on the amount of imbrication and armouring (Klingeman and Emmett, 1982). This is the process in which particles tend to interlock and align their long-axis parallel to the direction of flow which reduces the shear stress exerted upon them.

As the bedload transport rate varies in the direction of transport, successive locations experience either deposition or erosion. These variations will determine channel bed topography which in turn determines channel planform pattern (Ferguson and Werritty, 1983). Increased rates of bedload transport within a channel reach may cause scouring and incision leading to increased channel capacity and subsequent reduction in channel width (Richards, 1982). Likewise, in sections with lower specific stream power or larger sediment size, bedload transport capacity is reduced leading to within channel deposition. This results in a decrease in channel capacity and may subsequently cause channel widening by bank erosion, or where channel widening is restricted, incision or even channel avulsion may take place (Lewin, 1989). Lewin (1989) identified the process of "accretion catastrophe" whereby accretion within a channel causes the river bed to be elevated above the level of the surrounding floodplain eventually leading to avulsion. Werritty and Ferguson (1980) observed this process occurring on the River Feshie. They noted that the potential for channel switching lies in height differences and requires that active channels are aggraded and/or inactive channels are scoured.

Channel bed topography often dictates planform morphology by determining position and direction of channel thalweg. Two main types of channel bedform can be distinguished; those associated with pool-riffle sequences, and those associated with channel bars. Pool-riffle sequences are common in gravel-bed rivers. At low flow, pools are generally deep, slow-flowing with a gentle water surface slope and usually consist of fine sandy sediments. Riffles occur in wider sections of the channel characterised by rapid shallow flow, steep water surface gradient and sediments consisting of large gravel and cobbles. Pool-riffle spacing is often quite regular varying from between 5-7 channel widths (Keller and Melhorn, 1973). In straight channels, they usually show a meander-like alternation causing changes in thalweg direction and can lead to the initiation of channel meanders (Rhoads and Welford, 1991). In meandering channels, deep pools are often found on the outside of meander bends where they cause a convergence of channel thalweg with the concave bank leading to scour (Lewin, 1981). Intervening riffles are found on straight sections between meanders so that pool-riffle spacing in meandering channels is approximately half the meander wavelength (Lewin, 1981).

The presence of bars is one of the main factors in controlling the morphology of alluvial channels because they exert a strong influence on flow direction and sediment transport. Ferguson and Werritty (1983) identified two main types of in-channel bars:

1. Mid-channel - elongated in the downstream direction

a) Lobate - flow is radial over the curving sides,

b) Longitudinal - more elongated than lobate forms,

c) Diagonal - asymmetric across the channel.

2. Lateral - may have originated from mid-channel bars but are now attached.

Bars form in regions of reduced stream power where sedimentation exceeds erosion. Often, a channel blockage such as a fallen tree, will initiate sedimentation behind it leading to the eventual formation of a bar. Ferguson and Werritty (1983) studied bar development and associated channel change on the River Feshie and noted that episodic elongation and advance of channel bars by deposition can be seen as the cause for bank erosion and channel incision as a result of restriction in channel capacity.

2.7. Floodplain formation

Floodplains are formed by the in-filling of valleys by fluvial sediments. The character of a floodplain relates principally to the nature of the river by which it was formed; most simply, braided, meandering or straight. Lewin (1978), identified three basic floodplain types. The first type of floodplain, is dominated by overbank sedimentation and relatively stable channels. Sediments are generally fine grained and horizontally laminated, with coarser sediments closer to the channel and smaller amounts of finer sediments deposited at a distance.

The second type of floodplain, is characterised by relic point bar forms and actively meandering channels. Allen (1965) has described sediments associated with this floodplain type as, typically, a fining upwards sequence of cross-bedded sands and fine gravels produced by lateral point bar accretion. Sediments begin with coarse gravel and are topped with silts and clays deposited by overbank flows (see figure 2.4a).

The third type of floodplain is formed by multiple channels characterising braided rivers which produce a variable and complex morphology (figure 2.4b). The sediments have little internal organisation with a mixture of channel lag deposits, finer overbank deposits and cross-bedded bar material. Fining upwards sequences are rarely apparent and the sediments are usually poorly sorted.

Wandering gravel-bed rivers produce floodplains which have characteristics of both meandering and braided channels with relic point bar forms and numerous palaeochannels. Harvey et al. (1984), have demonstrated the complexity of morphological and sedimentological units formed by wandering gravel-bed rivers using a small reach of the River Carlingmill, England (figure 2.5).

2.8. Techniques of assessing river channel change

Techniques for studying river channel changes are many and varied. The method used for any particular study will depend on the following factors:

1. Timescale of study,
2. Purpose of study,
3. Scale of study, including the size of river and length of reach under investigation.

Perhaps the most important of these is the timescale of the study and under the headings of the three timescales used in this thesis is a summary of the most commonly used methods:

Geologic time - sedimentological evidence.
Geomorphic time - documentary records,
- map evidence,
- remote sensing,
- dating techniques; botanical methods,
Engineering time - field monitoring,
- remote sensing.

The details of these methods will be discussed in the following sections.

2.8.1. Sedimentological evidence; geologic timescale

Floodplain sediments hold a unique record of local historic fluvial activity. The most complete sedimentary records of former fluvial activity, are alluvial cut-offs which are abandoned river channels preserved by the processes of meander cut-off or avulsion. Many studies of sediments in alluvial cut-offs have provided researchers with valuable information of former channel conditions by examining factors such as cut-off dimensions (eg. Leeder, 1973), sediment sizes, sediment imbrication and infill stratigraphy (Baker et al., 1983). If the date of cut-off is known, then they also can provide records of flood load since cut-off formation (Erskine et al., 1992).

The study of river terraces can extend the record of fluvial activity further by examination of sedimentary deposits. Tipping (1994) for example, studied terraces in the Upper Bowmont Valley, Scotland to examine fluvial chronology and valley floor evolution. Brown and Keough (1992) studied palaeo-land surfaces and palaeo-channels to look at channel metamorphosis in mid to late Holocene deposits on the Rivers Nene, Soar and Severn.

2.8.2. Documentary records; geomorphic timescale

Hooke and Kain (1992) outline the types of documentary records which can be used. A good source is that of local newspapers which are often useful for their accounts of rare natural occurrences such as floods, landslips and important meteorological events. Local newspapers first appeared in the 18th Century but are often not useful for these purposes until the late 18th Century (Hooke and Kain, 1982). The accounts of events reported are often qualitative and subject to the enthusiasm and experience of the reporter. It is also necessary to know approximate dates of occurrence of the events otherwise it is a laborious job to sift through years of newspapers.

Another useful source of historical information is that of diaries kept by local enthusiasts. In the 18th and 19th centuries, there existed a breed of wealthy personages whose main interests were the exploration of scientific matters, particularly natural history. Diaries of such people are a wealth of often detailed and accurate information. Many societies were set up by these people whose proceedings are often invaluable sources of historical details. The Perthshire Society of Natural Science for example, published several in-depth accounts of historic flood events which occurred on the Tay river system, as well as reports on local geology, geomorphology, botany and zoology.

Agricultural and estate records can be an important source of land use history as well as documenting man's activities such as embankment building and gravel extraction (Hooke and Kain, 1982). Rivers were often used as estate or land ownership boundaries and consequently disputes over land rites often arose when river channel avulsion or meander cut-off took place. This often left one owner with less or inferior land and another better off and these disputes are sometimes well documented and provide an important source for dating channel movement episodes. Detailed graphical surveys may also be available which often shows positions of river banks although these are of varied and dubious accuracy (Hooke and Redmond, 1989).

2.8.3. Maps; geomorphic timescale

Maps are probably the most widely used source of data on the historical planform of rivers (eg. Werritty and Ferguson, 1980; McEwen, 1989; Hooke and Redmond, 1989). They can provide a wealth of information on the positions, dimensions and characteristics of river channels in the past as well as helping to date engineering works, determine the extent and nature of channel management and to assess the timing and nature of morphological adjustments (Hooke and Redmond, 1989). Often they are the only source of this type of information and although they have limitations they are valuable for providing information for the 100 to 150 year period which is beyond the scope of empirical observation (Hooke, 1977).

The limitations which arise with the use of maps are well documented by Hooke and Redmond (1989). One of the major problems is that maps provide "snapshots" in time and represent conditions that only apply at the time of survey. Changes between map dates therefore, have to be inferred or determined from supplementary evidence. Conditions at the time of survey are subject to water levels, differences in which can effect the representation of channel width and the nature and extent of channel bars. Another disadvantage in the use of maps is that they only represent the river in 2-dimensions, so that only information on river planform characteristics or network patterns can be established. Several necessary precautions must be adhered to when dealing with map data. Firstly, it is important to establish the appropriate map scale required for the study and this will relate to the size of the feature under investigation. Secondly, it is essential to assess the accuracy of the information portrayed in the map. This has important implications with regard to any quantitative measurements which may be derived from the map data. Errors may arise at any of several points in the process of map production. Firstly, errors may occur during data collection which is dependent on survey methods, equipment accuracy and also user error. Werritty and Ferguson (1980) when deriving braiding indices from Ordnance Survey maps from 1899 and 1971 found that apparent differences were due mainly to different survey techniques. This was because the 1971 map was based on large scale aerial photographs taken at a high river stage whereas the earlier maps were based on topographic surveys. Secondly, errors may occur during the transfer of information both in producing the original map and also in subsequent copying and editing. Finally, maps may become distorted during their use and storage due to the shrinking and stretching of paper (Hooke and Kain, 1982).

There are many methods which can be used to analyse map data. Again, Hooke and Redmond (1989) provide an informative review of such methods which they have divided into three categories; qualitative analysis of maps, quantitative analysis of maps and quantitative analysis from digital data. An examination of techniques of analysis under these headings follows.

Qualitative analysis of maps: This category includes a description of the location and nature of changes identified from superimposed maps and can show the extent of channel instability and the type of change. A classification of planform morphology can be achieved by visual interpretation of maps (i.e. braided, meandering or straight) although planforms may not always fit neatly into these categories and is also somewhat subjective. Werritty and Ferguson (1980) for example, used maps for a qualitative assessment of sinuosity and braiding on the River Feshie. Types of change can also be visually interpreted from the superimposition of different maps. For example, changes in meander morphology such as extension, translation, rotation etc. can be established. Dating and zoning of floodplains may also be interpreted from superimposed maps of different dates by comparing channel positions. This allows determination of the extent and locations of floodplain reworking.

Quantitative analysis of maps: The accuracy of measurements taken from maps is dependent on the scale and accuracy of the original maps. Measurements may be made of many channel reach characteristics such as length, width, sinuosity, number and length of bars and braiding indices. It is also possible to determine the distance of movement at various points and therefore rates of erosion (assuming this has been constant between map dates) and area of land reworked. Hooke (1977) used 1:2500 maps to measure movement of rivers in Devon. Tracings of maps were overlain and measurements were found to be accurate to plus or minus 7.5 metres or 1/4 to 1/3 channel widths. It is also possible to measure meander characteristics such as wavelength, amplitude etc.

Quantitative analysis from digital data: Hickin (1977) and Hooke (1977) digitised the centre lines of river channels to obtain computer based co-ordinates which could then be used to analyse meander parameters such as channel curvature and meander wavelength. At that time it was a laborious process and involved the use of punch cards. Computer technology has come a long way since then and the advent of Geographic Information Systems (GIS) has provided extended opportunities for digital analysis of river channel parameters and aspects of channel change. The exploration of the use of GIS in river channel studies is in its infancy but important studies by Gurnell et al. (1994) have provided valuable insights into the possibilities that GIS offers. There are several advantages with the use of GIS for the study of river channel changes:

1. Maps from different dates are often also at different spatial scales and through the use of map transformation and registration to a common base, accurate comparisons at a common scale are facilitated.
2. Data input to GIS systems is time consuming but once the information has been entered GIS provides an extremely flexible tool for data manipulation and analysis (Gurnell et al., 1994).

3. Information can be easily visualised without the constraints of traditional map boundaries. Also data classes can be stored in different layers and individual features may be assigned codes. GIS enables selection of different layers and codes thereby allowing a range of combinations of data to be analysed, visualised or output.
4. Quantification of error components is easier than that of manual methods (Gurnell et al., 1994).

Gurnell et al. (1994) use four different methods of data analysis. The first method, is simple polygon overlay whereby maps from two different dates are converted into raster cells and classified as channel or no-channel then superimposed onto one another. A quadtree cell can then be produced to compare how many cells can be classed as channel or no-channel for both map dates (Table 2.1) and this gives the number of cells either eroded or created by deposition during the period between the map dates. The second method used is that of multiple polygon overlay analysis. In this method, raster images of the river channel for a series of different dates are overlain, resulting in a map showing the cumulative period of occupancy for each grid cell. Thirdly, an area analysis gives values of area of occupation for the channel at various times. The last method is vector overlay mapping which is the simple comparison of overlain maps as would be done manually except the maps are scale corrected. This allows channel widths and positions to be measured as well as planform parameters assessed.

Table 2.1. Quadtree cell (Gurnell et al., 1994)

	Year 1		
Year 2		Channel	No Channel
	Channel	No Change	Erosion
	No Channel	Deposition	No Change

Gurnell et al. (1994) report the errors associated with using GIS. These arise from several processes during data input and manipulation. Firstly, there are errors associated with digitising the data and, secondly, errors may arise when the data is transformed to correct for scale and distortion. However, differences in channel boundary positions in excess of 5 metres are likely to result from a component of true channel planform change rather than errors introduced by data handling (Gurnell et al., 1994) which is a greater accuracy than that reported by Hooke (1977) of 7.5 metres, who used manual methods.

2.8.4. Remote sensing; geomorphic timescale

Aerial photography and remotely sensed imagery are extremely useful for detecting variations in floodplain character. Baker (1986) noted that remote sensing techniques are ideal for the delineation and reconstruction of palaeo-courses. Several studies concentrating on the floodplains of Indian rivers, have used satellite images to detect abandoned river channels (Ramasamy et al., 1991; Agarwal and Bhoj, 1992; Nagagjan et al., 1993). Philip et al. (1989), used Landsat MSS and TM images which were enhanced by linear contrast stretching and band ratioing to detect palaeo-fluvial features. Floodplain sedimentology has a strong influence on soil moisture content and this relationship was exploited by Davidson and Watson (1995) who used this as a surrogate variable for mapping fluvio-sedimentary features. Lewin and Manton (1975) and Lewin and Weir (1977) used photogrammetry on aerial photographs to contour 3-dimensional floodplain features including scroll bars used to determine the evolution of a meander loop.

2.8.5. Dating techniques; geomorphic timescale

Dating techniques useful within this timescale are mainly botanical such as dendrochronology and lichenometry. Dendrochronology involves the counting of tree rings taken as cores from trees. Petts (1977) and Harvey et al. (1984) used this method to determine minimum ages of bench features. Lichenometry relates the age of lichens to their size thus allowing the dating of exposure of the substrate on which it grows. Lichens can also be used as a reasonably accurate indicator of river channel capacity (Gregory, 1976; Gregory, 1977).

2.8.6. Field monitoring; engineering timescale

Field monitoring perhaps provides the most detailed and accurate studies of river channel change. The use of field monitoring is however, restricted spatially and temporally due to its labour intensive nature. Ferguson and Werritty (1980) note that the simple extrapolation from short-term field survey is hazardous in that the record of channel events may have been atypical and unrepresentative of long-term trends. Field observations are however, useful for studying underlying processes as long as studies of channel change are also examined in a wider context.

Many studies using field survey techniques examine the nature and distribution of bank erosion. The use of erosion pins is one of the most widely used methods for studies of this sort (eg. Wolman, 1959; Hooke, 1977; Brookes, 1987) whereby a series of metal rods are inserted horizontally into the river bank flush with the surface, and their subsequent exposure gives a detailed measurement of rates of erosion. The success of this method relies on the rate of retreat being less than the length of the rods and also assumes that the rods do not locally modify bank cohesion (Richards, 1982).

Another method widely used for studying channel change is that of repeated profile surveys on monumented cross-sections of the river or by repeated plan surveys which may be compared with maps or aerial photographs (e.g. Werritty and Ferguson, 1980; Ferguson and Werritty, 1983; Brookes, 1987).

Sediment transport rates may be studied in the field in a number of ways. The most common of these is the use of sediment traps which are placed in the river bed and sample the amount of near-bed sediment passing through a cross-section of the channel (eg. Richards and Milne, 1979; Reid et al., 1980). Sediment transport patterns are mainly studied with the use of tracers. These are sediments which have been naturally or artificially labelled with for example, fluorescent paint coatings or they may be magnetically or radioactively tagged. Schmidt and Ergenzinger (1992) for example, used magnetically tagged pebbles to examine the variations in transport rates of differently shaped bedload particles.

2.8.7. Remote sensing; engineering timescale

Many short term studies of fluvial change have been aided by the use of aerial photographs which have been widely available since World War II. These may be used purely for visual interpretation of channel change (Ferguson and Werritty, 1983) or scale corrected for direct comparison. Werritty and Ferguson (1980) used a Bausch and Lomb zoom transferscope to overlay data from several aerial photographs of different dates although this method was not found to be accurate enough for quantitative comparison. The GIS techniques for the analysis of maps as reported in section 2.6.3. are also applicable to remotely sensed images and aerial photographs. Differences in scale and distortion can be rectified by the transformation of data so that photographs of different dates can be accurately compared with each other and also with conventional maps. Gurnell et al. (1994) digitally scanned aerial photographs which were then geometrically corrected and registered to an Ordnance Survey base map. Bank lines could then be digitised and used for comparison and analysis.

Satellite images have also been used for the short term monitoring of river channel changes. Salo et al. (1986) used multi-date Landsat MSS images of the Rivers Ucayali and Amazon in Peru to quantify lateral migration rates.

Riparian vegetation is an important control on channel change and remote sensing provides a powerful technique for its classification and monitoring. Hooper (1992) used ATM (Airborne Thematic Mapper) data for assessing vegetation in, and along the Rivers Exe and Teme to determine an innundation gradient in vegetation types. Hewitt (1990) used Landsat TM data successfully to map marginal habitats of the Yakima River in central Washington.

2.9. Previous geomorphic studies in Scotland

The landscape of Scotland has given rise to some interesting and dynamic rivers. However, relatively few studies have explored the geomorphology and regimes of these rivers. The notable exceptions are detailed below. McEwen (1986; 1989) examined channel changes on the River Dee in response to flooding over the last 200 years and has also documented flood histories and chronologies for the Rivers Dee and Tweed (McEwen, 1987a; 1987b; 1990). Lewin and Weir (1977) detailed the morphology and history of the River Spey over the last 200 years. The study of channel changes and gravel bar development on the River Feshie has produced two notable papers (Werritty and Ferguson, 1980; Ferguson and Werritty, 1983) and a headwater tributary of the River Tay (the Allt Dubhaig) has been examined for slope induced changes in channel characteristics (Ferguson and Ashworth, 1991). In addition, two studies on the impact of flash flooding have been published (Werritty, 1984, McEwen and Werritty, 1988). Of these studies, perhaps the most relevant to this research, are those of McEwen (1989), Werritty and Ferguson (1980), Ferguson and Werritty (1983) and Lewin and Weir (1977). Although some of the findings of these studies have been discussed in previous sections, the main conclusions of these works are summarised below.

McEwen (1989) examined channel changes over the last 200 years on the River Dee by comparison of the first and second edition OS maps. Braiding indices showed a high degree of variability between reaches and the author suggests that local controls such as availability of sediment and bank erodability are important. Between 1869 and 1902, McEwen (1989) found a general increase in braiding indices but a major decrease between 1902 and 1971. The author suggests that the increase in braiding index (1869 to 1902) may have been a result of a moderate increase in extreme flooding around the 1880s and 1890s. The decrease between 1902 and 1970 may have either been due to the decrease in frequency of extreme flooding or a result of localised channel alteration such as embanking. McEwen (1989) also found extreme floods (>100 years RI) to cause major morphological changes along the River Dee provided that the channel was relatively unconfined. Lesser floods (10 to 50 years RI) were found to be important for returning the channel to quasi-equilibrium.

Werritty and Ferguson (1980) studied channel changes on the River Feshie over timescales of 1, 30 and 200 years. The River Feshie with a channel slope of 0.01 and a mean discharge of 8.1 m^3s^{-1}, is potentially braided throughout its length. However, only three reaches exhibit a braided pattern whilst the other reaches are restricted by high terraces or bedrock (Werritty and Ferguson, 1980). Between 1899 and 1971 an increase in braiding occurred with an associated decrease in meandering and an increase in the extent of bare gravel. The authors noted that braiding occurs in response to flooding with a subsequent increase in meandering with recovery of channel pattern. The presence of nodes was also noted along the main channel, which remained relatively stable and were associated with initiation or termination of channel switching (Werritty and Ferguson, 1980).

Ferguson and Werritty (1983) also examined bar development on the River Feshie and associated channel changes. Although no single pattern of bar development was found, some generalisations could be made. Unconfined reaches underwent more complex changes as a result of rapid erosion of both banks in response to bar formation or accretion. However, the development of a meandering pattern resulted from localised bank erosion caused by alternate channel bars (Ferguson and Werritty, 1983). The River Feshie has a transitional pattern whereby stream power and river bank erodability are closely balanced so that the river does not develop far along the divergent paths of meandering or braiding. Braided channels occur after a major flood and meandering channels result from a prolonged absence of flooding.

Lewin and Weir (1977) examined the morphology and recent history of the lower River Spey. They found the floodplain at this location to be composed of three main zones. The first comprised the active channel which was meandering with gravel bars on the inside of bends. Braiding was a low stage phenomenon. The second zone consisted of scrub and inactive channels at low flows. Woodland was developed on areas of finer sediments and those that had been abandoned for the longest times. The third zone was older than two hundred years and showed no recent channel activity. In an examination of the 1876 first edition OS maps of the area, Lewin and Weir (1977) found a greater degree of channel braiding than that exhibited by the recent morphology of the River Spey. The channel in 1876 had a greater number of larger bars, often without a single dominant channel (Lewin and Weir, 1977). The authors suggest that the marked decrease in braiding was probably a result of human activity mainly through afforestation and bank protection works which have restricted channel mobility during flood events.

The consensus of opinion shown by these studies is that these upland gravel-bed, Scottish rivers show a transitional pattern. Partial braiding results from large flood events whilst subsequent events simplify the channel pattern. Individual reaches respond in different ways to flood events with unconfined reaches exhibiting a greater degree of channel change. In addition, two of the studies (McEwen, 1989; Lewin and Weir, 1977) describe large decreases in braiding indices between circa 1900 and the 1970s which is possibly attributable to a decrease in the frequency of large magnitude events or by channel alteration and confinement. However, Werritty and Ferguson (1980) describe an increase in braiding index along the River Feshie during this period even though much of this river is unconfined.

2.10. Previous geomorphic studies on the River Tay

Despite being the largest river in Britain, surprisingly little is known about the geomorphology of the River Tay. The few studies that have been undertaken were little more than observations following major flood events in the 19th and early 20th centuries. These papers were written by enthusiastic amateurs living close to the River Tay but provide detailed and accurate accounts. A summary of the reports of flood events published in these proceedings is provided by Mr. C. MacIntosh of Inver (1909). Henry Coates made detailed studies on the geomorphology of the Rivers Tummel and Tay from Tomdachoille to the bottom of Lamb Island. Details of his studies were published in two papers, the first of which (Coates, 1906) describes in detail the transition of an area from a shingle bar to vegetated meadow land which now forms part of the floodplain at Ballinluig. Descriptions of vegetation successions and the infilling of backwaters are given as well as a detailed geomorphological map of the river. The other paper (Coates, 1914) describes the evolution of plant life on a haughland which includes accounts of the numbers and types of species found on the haughlands, islands, shingle bars and back waters.

Apart from several studies of sediment transport on the River Tay and some of its tributaries (Al-Ansari, 1976; Al-Jabbari, 1978; Al-Jabbari et al., 1980) no other work was undertaken until the extreme flood event of 1990 spurred several studies into action. A detailed report commissioned by Tayside Regional Council was carried out by Babtie, Shaw and Morton, Consulting Engineers (1990). The report documented the damage sustained in rural and urban areas, hydrological conditions prior to and during the flood, factors affecting run-off and also explored possible flood alleviation measures for future development.

A study of a major embankment breach at Caputh on the River Tay during the 1990 event, is reported by Gilvear and Harrison (1991). The formation of two new channels is explored in relation to the position of former river courses and proposes that lower floodplain elevation and the occurrence of sand and gravel deposits along abandoned channels causes these areas to be more vulnerable to erosion.

Gilvear and Winterbottom (1992) use the analysis of old maps and documentary sources to examine historic channel changes on the Rivers Tay and Tummel between Pitlochry and Dunkeld. Documentary sources reveal that flood damage during the 1990 event occurred in similar locations to those which sustained damage during previous documented events. Through the use of old maps, stable and unstable (sedimentation zones) sections of the river are provisionally identified. Historically unstable sections relate to areas which suffered the most damage during the 1990 flood event and many of the embankment breaches were found to have occurred where they overlie old river channels.

Conservation and river management issues relating to river channel instability are discussed by Gilvear (1993). In the paper, it is proposed that unstable river sections have a high conservation value due to the diversity of habitats. It is also suggested that flood embankments should be placed around rather than across these unstable zones, firstly to decrease the risk of flood damage and secondly to allow channel movement within these areas and so preserve the habitat diversity.

The flood event of 1993 resulted in further studies of the River Tay. Babtie, Shaw and Morton, Consulting Engineers (1993) were again commissioned by Tayside Regional Council to produce a report of the flooding which focused on flood mitigation measures for protecting the urban areas in and around Perth. A catchment study was also undertaken by Ove Arup and Partners, Consulting Engineers (1994) which examines hydrological trends and reports the production of a hydrologic model for the catchment.

Gilvear et al. (1994) identified embankment breaches resulting from the 1993 flood, using pan-chromatic aerial photography. The breach locations were compared with those of the 1990 flood event and there was found to be a high level of coincidence. Specific sections that had high numbers of breaches were either in historically unstable reaches where embankments overlay old channels, or where embankments were on the outside of meander bends. Other breaches occurred more as a result of local factors such as scour around fences or poor embankment construction.

CHAPTER 3

HISTORICAL EVALUATION OF CHANNEL CHANGE AND FORMER FLOOD EVENTS ON THE RIVER TAY

3.1. Introduction.

The historical study of river channel change is important for many reasons (eg. river management, floodplain hazard zoning etc.). The flooding of the River Tay in 1990 and 1993 showed evidence that certain sections of the river were more unstable than others. Furthermore, an examination of archive sources established that these sections of river had historically been more sensitive to change (Gilvear and Winterbottom, 1992). Hooke and Redmond (1989) pointed out the value of using historical evidence to establish whether a reach of channel has been stable or not over certain time periods and it can also be used to define stable and unstable reaches. Furthermore, they noted that if the purpose of study is the prediction of future changes it is much more valid if an historical perspective is taken rather than relying on contemporary observation. A detailed study of historical channel changes is, therefore, thought to be useful to identify stable and unstable reaches and to examine more detailed morphological changes within these reaches in order to determine typical patterns, mechanisms and rates of change.

Historical channel change on the study reach is investigated via the use of map information which dates back to 1755. GIS techniques for data comparison are employed for this part of the study which is described in section 3.2. and the analysis of maps using GIS is discussed in section 3.3.

The historical study of channel change is typically confined to the time-scale dictated by the availability of accurate map information. In section 3.4., the application of remote sensing techniques for investigating areas displaying landform evidence of channel activity prior to the earliest map date covering the study reach, is explored and the usefulness of the information gained by the employment of these techniques is discussed.

A comparison of embankment breaches during the 1990 flood on the Tay and those of previous historical events revealed that many occurred repeatedly in the same or similar locations (Gilvear and Winterbottom, 1992). In the same study, it was also proposed that the breaches apparently occurred where flood embankments overlay abandoned river channels. The effects of historical flood events and the locations of documented embankment breaches are detailed in section 3.5.

Section 3.6. examines long term rainfall trends so that identified channel changes may be placed in context with contemporary climatic conditions. Section 3.7. is a discussion of results and section 3.8. concludes the chapter.

3.2. The comparison of maps using GIS techniques

Typically, comparison of map data to identify channel change has been made by manual overlaying of the maps. This presents major problems when the available maps are at different scales and the area of interest extends over several different map sheets. The use of a Geographic Information System (GIS) with its ability to scale correct and superimpose different maps with great precision appears to be the ideal tool to make these comparisons. It also allows the production of seamless maps and the selection of any combination of data for output or analysis. In addition, measurement of channel dimensions can be made to a level of accuracy that is difficult to achieve using more traditional sources.

3.2.1. Map availability

The first full map coverage of Scotland is Roy's Military survey 1747-1755, which was undertaken to facilitate English military activity in Scotland, after the Jacobite uprising. The surveying was carried out during the summer months using theodolites with "common sites unaided by telescope" and chains of between 45 and 50 feet in length (Moir, 1973). The completed map which is reproduced at a scale of 1:36000, has been described by Moir (1973) as "reasonably accurate". However, William Roy in 1785 said of the survey that, due to the rudimentary equipment used and the lack of funding it is "to be considered more as a magnificent military sketch than a very accurate map of the country" (quoted by Moir, 1973). It does however give us some idea of the channel planform at this time, particularly as military routeways tended to follow the natural courses afforded by valley bottoms.

Stobies Map of Perthshire (1783) was the next map of this area to be produced but the accuracy is relatively poor. In 1866/1867 the first Ordnance survey maps at a scale of 1:10560 of the area were produced (surveyed 1863) and these provide the first reliable maps from which it is possible to make accurate quantitative comparisons with later maps. The second edition OS map of the area, was published in 1900/1901 (surveyed 1898/1899). Four separate maps from the 1:10000 series are needed to cover the study reach (NN95NE, NN95SE, NN94NE and NO04NW). The two southern maps of the area were revised for changes in 1976 and the two maps of the northern area were revised in 1989 and 1990. However, visual comparison of the 1976 maps with aerial photographs from 1988 and 1992 show that no significant changes occurred during the intervening period in this length of the river.

3.2.2. Conversion of maps to digital data

Laser-Scan software running on a DEC micro-Vax with a Sigmex 9000 graphics terminal and an TDS A0 digitising table, was used in this study. The digitising and map editing package by Laser-Scan, Lites2 (Laser-scan InTeractive Editing System - 2nd generation) was used for the digitising, display and editing of map data which was input as vector files. It allows the use of different feature codes and layers for different types of information each of which can be selected individually for display or output. Additional information can be attached to vectors as attribute codes which can also be used for selection.

Firstly, however a map template must be created. This was achieved using Laser-Scan's Istart package which creates an Internal Feature File (IFF) as a pre-digitising template. This enables the user to specify information relating to the map which is stored in the map descriptor. In OS (Ordnance Survey) mode, the user is prompted to input OS (UK) specific information relating to the map scale, map extent, grid step and origin offset. The projection, spheroid and units are set to the following defaults;

Projection - transverse mercator (UK. National Grid)

Spheroid - airy

Units - metres

IFF files for the 1:10000 series Ordnance Survey maps were set up with the following input parameters:

Scale - 1:10000

Map extent - 5000 by 5000

Grid step - 1000

Origin Offset - input as the eastings and northings of the south-west corner for each map, ie. NN95NE - 295000 755000, NN95SE - 295000 750000, NN94NE - 295000 745000, NO04NW - 300000 745000.

Selected information from each map was then carefully digitised. Only features of the river corridor were thought relevant to this study so a strip of information either side of the river was digitised with the A9 as the eastern boundary and the edge of the floodplain (where a major break of slope occurred) as the western boundary. Table 3.1 shows the information digitised from these maps, the layers into which they were put and the feature codes used.

Table 3.1. Layers and feature codes used for information digitised from the 1:10000 OS maps.

Layer Number	Feature Code	Information
0	398	Ordnance Survey grid.
2	1	River boundary (represented on Ordnance Survey maps as "normal winter levels" (Harvey, 1975)).
3	25	River embankments.
4	33	Railway line.
5	3	Roads (with no definition between major and minor roads).
6	14	Field boundaries.

When the relevant information from the four maps had been converted into digital data, they were merged together, using Laser-scan's Imerge package, to create one file. This package uses the origin offset information contained in the map-descriptor to join the maps together in their correct positions. The combined map was then used as a base map to which all others could be rectified.

Following the input of the 1:10000 maps, Roy's Military Survey (1747-1755) was digitised. Copies of this map are held by the National Library of Scotland (map section). Sheet 17/2 covers the whole of the study area. Borrowing of these maps is not possible and so another method of copying was necessary. Hooke and Redmond (1989) suggest that the easiest method of copying maps under these circumstances, is to trace them using stable tracing paper as other forms of copying or reproduction such as photocopying, are likely to incorporate distortion. The river planform outlines on the map were carefully traced. It is important when using maps for comparison, that as many fixed reference points as possible be included so that other maps may be matched up using these points. The location of fixed reference points on Roy's map was a major problem as there were very few floodplain structures built at the time of the survey. It was also difficult to assess whether the structures marked on the map were the same buildings as those marked on recent maps. In addition, the buildings on the more recent maps are represented in their true shape and dimensions whereas the buildings on Roy's maps were represented as simple squares or dots. For this reason, as well as survey inaccuracies, this map is not suitable for accurate comparison but it was felt however, that some advantages may be gained from attempting to rectify and scale correct this map to the base map in order to obtain an approximate indication of the river's position and planform at that date.

The channel planform was digitised from the tracing of Roy's map along with the locations of any points of reference. These reference points were then used to rectify and scale correct the map data to fit the base map. Laser-scan's package Itrans has several functions, one of which is for the transformation of data from one co-ordinate space to another when the mathematical relationships between them are not known but the values of several common points in each system are (Laser-scan, 1990). Co-ordinates of the original points are input with the co-ordinates of the target points. Five sets of transformation formulae are available in the Itrans package. Throughout the study, each of these sets were tested for the best results by visual comparison and also by measuring differences at fixed reference points between the corrected maps and the base map. The four point transformation gave the most consistently accurate results and so was the transformation used throughout this study. This method uses a least squares fit of the sets of co-ordinates to compute the transformation:

$$X=a1+a2*x+a3*y+a4*x*y \tag{3.1}$$

$$Y=b1+b2*x+b3*y+b4*x*y \tag{3.2}$$

It requires a minimum of four control points which will be forced to fit the output points exactly. When additional points are given, a least squares solution is applied to these. Where the maximum of these discrepancies is greater than 1/1000th of the range of the target control point values then the user is asked if the transformation is accepted (Laser-scan, 1990). Residual values are displayed so that the error can be quantified. This method produces accurate results as long as the control points are accurate. Large errors may be reduced by discarding rogue control points and/or by selecting more reliable points.

The results of the rectification of Roy's map are of low accuracy as was initially expected due to the inaccuracies of the original survey, the poor quality of map reproduction from which the outlines were traced, and also because of the lack of control points for the map transformation. Figure 3.1a, b and c show Roy's map transformed, rectified and overlain onto the 1:10000 base map which has been split into three sections so that it may be output at a larger scale.

The 1st and 2nd edition Ordnance Survey 1:10560 maps (surveyed 1863 and 1899; published 1866 and 1900 respectively), are also available at the Edinburgh Map library but again, the borrowing of these maps was not allowed and so they were carefully traced. The river outline, islands, gravel bars, areas of marshy vegetation on the floodplain and abandoned channels were digitised from the tracings of the two sets of maps. The grid lines on these maps are at intervals of 1' longitude and 30" latitude. Although the 1:10000 series maps are divided up by the National Grid, the positions of latitude and longitude are still given on the map margins. From these positions it was possible to construct a grid on the 1:10000 maps which corresponded to the same grid as on the 1:10560 maps. The intersections of these grid lines could be used as control points for the scale and position rectification of the 1:10560 maps using a four point transformation as previously described. The rectified maps overlain onto the 1:10000 base map can be seen in figures 3.2a,b,c and 3.3a,b,c.

3.2.3. Accuracy assessment

When using maps for taking detailed measurements it is important to consider spatial errors. In this study errors likely to be incorporated into the final rectified maps, may originate during the following stages:

1. the initial survey,
2. the transfer of survey data in map production,
3. distortion of map due to the expansion and shrinkage of paper,
4. the tracing of maps,
5. digitising the tracings
6. rectification of maps.

It is difficult to assess the amount of error that each of these stages produces. However, errors in the initial survey have to a degree, been addressed by the Ordnance Survey. The Ordnance Survey maps were the first maps which were produced with an acceptable level of accuracy for measurements to be taken. However, there are errors in these which must be considered. After 1970 the Ordnance Survey started to conduct regular testing of map accuracy. This was achieved by independent survey of a series of points represented on the Ordnance Survey map. The co-ordinates of these points were compared and the root mean square error is calculated in metres on the ground. For the Ordnance Survey 1:10000 series the acceptable level of accuracy is 3.5 metres root mean square error (Harley, 1975).

As well as the inherent inaccuracies in the map from the initial survey and reproduction, distortions in the paper on which the map is printed can occur. Map paper will shrink or expand slightly depending on how it is stored (Hooke and Redmond, 1989). This is extremely difficult to quantify however, and due care must be taken in the handling and storage of maps.

In the past, errors in the tracing, digitising and rectification of maps have also been difficult to quantify. However, one of the advantages of using GIS, is that highly accurate measurements between points is possible. This facility was utilised to assess the accuracy with which the rectified maps could be compared with the base maps. Fixed reference points which could be identified both on the base map and the rectified map were located and their co-ordinates on both maps were noted to the nearest 0.1 metre. The difference between the co-ordinates (base map minus rectified map) were determined for x and y. Firstly, the systematic error was calculated as given by the equation:

$$s = \frac{\sum x}{n} \tag{3.3}$$

If s=0, then the errors are random. If however, a systematic error has been introduced into the data (most likely during map rectification), then the value of s will give the amount of "shift" which has taken place.

Secondly, the root mean square error was calculated. This is expressed as:

$$r = \sqrt{\frac{\Sigma x^2}{n}} \qquad (3.4)$$

where x_1, x_2, ..x_n, are the errors at n reference points. This value is the average amount by which co-ordinates of the same point on the two maps, will deviate. This error must be considered when taking measurements of change that have occurred between the two map dates.

Error measurements for the 1st and 2nd edition Ordnance Survey maps were made using the 1:10000 series map as a base map from which error margins were measured. The results are given in table 3.2.

Table 3.2. Errors determined for the rectified 1st and 2nd edition Ordnance Survey maps.

Error Type	Systematic		Root mean square	
Direction	X	Y	X	Y
Error between 1st edition OS and base map (metres).	-0.1	0.9	3.0	3.5
Error between 2nd Edition OS and base map (metres).	-0.6	1.5	3.3	3.2

As well as spatial errors, the problem of temporal errors must be noted. Ordnance Survey maps can have as many as three dates; one for the original survey, one for revision or resurvey and one for publication. Survey dates must be treated as approximate especially for older maps where dates and areas of revision are not always given or where boundaries from previous surveys are carried over without acknowledgement (Carr 1962).

3.2.4. Discussion

Roy's map, as shown in figure 3.1a, b and c, although of a low accuracy, shows the river at this time to consist of multiple channels and mid-channel islands. Only three small sub-reaches are shown as single-thread (reach 1 in figure 3.1b. and reaches 2 and 3 in figure 3.1c.). The River Tummel has a more multi-thread character and complex planform than the length of the River Tay within the study reach, which occupies a smaller width and contains the three defined single thread reaches.

Figures 3.2a, b and c, depicting the river channel in 1863, show a similar but more accurate picture of the river channel planform. Again, the River Tummel is a multi-thread channel with a number of mid-channel islands although there appear to be less than the number depicted on Roy's map. There are four single thread sections, three of which are the same as those shown in Roy's map, the other is labelled reach 4, in figure 3.2b.

The river channel in 1899 as shown in figures 3.3a, b and c, is much the same as that of 1863, but with perhaps slightly fewer multiple channels as a result of the increase in size, or fusion of the mid-channel islands. The four single thread sections in 1863 (see figures 3.1. and 3.2.) are also single thread in 1899.

In marked contrast, the river planform in 1975 shown in figures 3.1., 3.2. and 3.3. for comparison with Roy's map and the 1st and 2nd Edition Ordnance Survey maps, is distinctly single-thread and has a narrow channel width. The few mid-channel islands on the map, support mature stands of vegetation indicating a relatively lengthy period of stability.

Taken together, the maps shown in figures 3.2. and 3.3. indicate that over a 112 year period (1863 to 1975), some sections of the river are characterised by divided sections which have changed planform over time, whilst other sections have remained relatively stable and single-thread.

3.3. Data analysis of map information

The presence of stable and unstable sections was discussed in section 3.2.4.. On the basis of these, the study reach was divided up into sections designated by separating nodal points. These nodal points are defined as having remained in fixed positions throughout the period of investigation and divide the single and multi-thread reaches. This resulted in the delineation of 10 sections (figures 3.4a to j), 6 of which could be classed as unstable (ie. those that have exhibited marked changes in planform between 1863 and 1975) and 4 as stable (ie. sections which have remained single thread reaches between 1863 and 1975). Sections 1, 2, 4, 6, 8 and 10 are unstable; sections 3, 5, 7 and 9 are stable.

Using GIS facilities, measurements for each section were made of active gravel area (this included all mid-channel and lateral bars which were not shown as vegetated on the maps), average channel width (calculated as the sum of channel widths taken at approximately 100 metre intervals divided by the total number of measurements), sinuosity (defined as channel length at mid-channel, divided by down valley length) and braiding index as defined by Brice (1960):

$$B_I = \frac{2x total\ length\ of\ bars\ within\ reach}{reach\ length\ at\ mid - channel} \qquad (3.5.)$$

Only vegetated islands were used to calculate the braiding index so that errors due to different water levels during the survey, did not affect the results. This does mean however, that the braiding indices calculated maybe somewhat misleading, as bars within braided channels are seldom vegetated due to their dynamic nature. Tables 3.3, 3.4 and 3.5 show the results of these analyses which are graphically represented in figure 3.5.

Table 3.3. Active Gravel Area (metres^2) 1863 to 1975.

Section Number	1863	1899	1975
1	285832	192896	193669
2	371991	365244	232842
3	46737	48136	42109
4	225854	271378	121233
5	98051	98532	95847
6	412899	372716	184489
7	117320	99462	78756
8	153028	120062	73922
9	62441	61237	58127
10	213268	223324	122803

Table 3.4. Average channel width (metres) 1863 to 1975.

Section Number	1863	1899	1975
1	185	122	111
2	123	120	85
3	83	84	71
4	187	241	76
5	126	128	119
6	215	192	112
7	119	100	74
8	154	110	77
9	91	88	82
10	164	145	89

Table 3.5. Channel Sinuosity and Braiding index. (S = sinuosity, B.I.= braiding index)

Year	1863		1899		1975	
Section number	S	B.I.	S	B.I.	S	B.I.
1	1.10	0.46	1.12	1.43	1.12	-
2	1.21	0.56	1.22	0.29	1.09	0.11
3	1.00	-	1.01	-	1.03	0.50
4	1.13	1.66	1.06	1.57	1.06	-
5	1.00	-	1.00	-	1.01	-
6	1.15	1.87	1.15	1.77	1.16	-
7	1.02	0.81	1.02	-	1.02	-
8	1.06	-	1.06	1.13	1.10	0.69
9	1.00	-	1.00	-	1.00	-
10	1.07	0.97	1.08	1.22	1.05	-

3.3.1. Discussion

Sections 1, 2, 6, 7, 8 and 9 all show decreases in active gravel area and average channel width between 1863 and 1899. Sections 3, 5 and 10 show a slight increase in active gravel area but with either little change or a decrease in the average channel width. Only section 4 shows a marked increase in both these parameters. No distinct pattern can be established for changes in braiding index and sinuosity during these dates although most sections showed little change. Between 1899 and 1975 all sections showed a decrease in both active gravel area and average width with most sections showing a substantial decrease in these factors. In the unstable sections, this was accompanied by a decrease in the braiding index and in most cases, little change or an increase in sinuosity. The stable sections, have low sinuosities and braiding indexes which changed little.

3.4. Remote sensing of old river channels

Prior to the 1st edition Ordnance Survey map, there is little accurate evidence on the positions of old river channels and reaches of instability. Historical estate plans do provide some information but they are difficult to piece together because various estates owned the riparian land. The plans were also surveyed using different scales and techniques, and some are no more than approximate drawings, so an assessment of accuracy is difficult. The 1st Edition Ordnance Survey maps of the study area were produced after the river embankments and railway were built. In consequence, they do not allow all the areas of historical instability to be fully assessed as they only show the river in its confined state. It is important therefore, to determine whether embanked sections were unstable prior to channelisation. Roy's map provides some information, but with the use of remote sensing methods it may be possible to extend the record.

The use of aerial photography and remotely sensed imagery to determine the positions of old river channels has been discussed in chapter 2 (section 2.8.4.). In June 1992, NERC carried out an airborne survey of the study area to acquire Daedalus ATM imagery (for details see Appendix A). The result of the 1992 survey was a set of false colour, infra-red photographs (approx 1:10000) and ATM (Airborne Thematic Mapper) imagery of the study area. The ATM imagery consists of 11 spectral bands (see Appendix A for details) with a spatial resolution of approximately 2 metres on the ground. Davidson and Watson (1995) used the ATM imagery to investigate the relationship between reflectance values and floodplain sediment characteristics. Their research demonstrated that reflectance in band 11 (thermal infra-red, 8.50 - 13.00mm) is strongly correlated with soil moisture content. Given that soil moisture content is related to sediment characteristics and that, on the floodplain, these are in turn related to palaeo-fluvial activity, it follows that the spatial variation in band 11 can be related to palaeo-channel patterns as demonstrated by Davidson and Watson (1995).

3.4.1. Method

The ATM imagery was divided into a number of 512 x 512 pixel images each of which included a strip of the river and, where possible, part of the floodplain on either side. These smaller images were "cut out" using a program written by Dr. A.I. Watson of the

Environmental Science Department, University of Stirling. The use of these smaller images allowed easier data manipulation and more accurate image rectification. Eleven images covered the area from the downstream end of Lamb Island to the northern limit of the study reach. The line of imagery covering the area downstream of this had experienced some 'drop-out' whereby several lines of the scanner did not record data. Although the river in this area was covered, most of the western side of the floodplain was affected by the drop-out. This precluded the delineation of floodplain features and also obscured important ground control points needed for image rectification. Therefore, it was decided that the infra-red photographs would be used to study the palaeo-sedimentary features on the floodplain for this part of the study reach. This would also allow a good comparison of the use of the two methods for this purpose.

The band 11 images were processed using the R-Chips image processing package. This was run on a IBM compatible 386 PC. Figure 3.6a shows an example of a raw, unprocessed image of an area of the floodplain on which many palaeo-fluvial sedimentary features can be seen.

Image display and recording systems usually operate over a range of 256 greyscale levels (0-255). However, in an image, greyscale levels rarely extend over this range, resulting in a low contrast. In order to improve the visual appearance of the images, a contrast stretch was applied. This reassigns the pixel values so that the entire range (0-255) is used. There are two methods which may be used to achieve this. Firstly, a simple linear stretch will reset the minimum and maximum values of the image to 0 and 255 respectively. Intermediate values remain in the same relative positions but are linearly mapped onto the new range.

Alternatively, a linear stretch with saturation points can be used. In this method, the frequency distribution of the data is calculated and the 5th and 95th percentile is reset to the minimum and maximum values. This is useful for optimising the contrast of the main body of the data and is not affected by stray high or low values. A linear contrast stretch with saturation points was applied to the images.

In order to further enhance the images for improved visual interpretation, an edge enhancement filter was used. The use of this filter enhances the boundaries between regions of contrasting brightness by increasing the brightness of pixels that are already brighter than the local average and decreasing the brightness of pixels that are already darker than the local average (Campbell, 1987). The filter is a 3x3 kernel which is passed over the image. Each image pixel and its eight surrounding neighbours are multiplied by the values in the filter template which are as follows:

$$\begin{matrix} -1 & 0 & -1 \\ 0 & 5 & 0 \\ -1 & 0 & -1 \end{matrix}$$

The resulting values are summed to give a new value for the centre pixel. Figure 3.6b. shows the example image which has been processed in this way.

The outlines of the sedimentological features and the positions of identifiable control points were digitised as overlays of the images and saved as separate files. These were then transferred onto the micro-Vax and converted into DTI files (Laser-Scan's format for raster data files) using a conversion program written by Dr. A.I. Watson. The data contained in the raster files was subsequently converted into vector data using laser-Scan's Vectorise package. The control point information from the image files and from the maps to which they would be rectified, were stored in a data file. This allowed these files and any subsequent data taken from the original ATM images to be geometrically corrected using the same control points. The data rectification was achieved using a four point transformation as described in section 3.2.2.. The average root mean square error for the rectified data is 5.4 metres in the x direction and 8.5 metres in the y direction.

For the southern part of the study reach floodplain, the infra-red photographs were used to study the sedimentary features. These features were less evident on the photographs than on band 11 of the imagery, but more obvious than on conventional black and white aerial photographs. Plate 3.1. shows an example of the infra-red aerial photography with sedimentary features visible. These were digitised directly from the aerial photographs and the data was then rectified to the base map using a four point transformation of ground control points. The average root mean square error for the rectified photographs is 3.9 metres and 3.6 metres for x and y, respectively.

Around the time that the imagery was acquired, areas of very high and very low reflectance in band 11 were investigated in the field. Several points within each of these feature types, were located and the sediments were examined with the use of an auger.

3.4.2. Results

Figures 3.7a, b and c are resultant maps of the whole study area which show the outlines of the palaeo-fluvial sedimentary features taken both from the imagery and the aerial photographs.

The field study of sediments in areas of very low reflectance showed that they consisted of silty clays or sands as would be expected in low energy environments such as infilled abandoned channels. Areas of very high reflectance were found to have coarse gravels and cobbles at the surface so that augering through these sediments was not possible.

3.4.3. Discussion

The data derived from the remote delineation of palaeo-fluvial sedimentary features, may be used for several purposes. Firstly, it allows the determination of the parts of the floodplain which have been formerly active as can be seen on figures 3.7a, b and c. It also enables the examination of historical stability over a longer period than covered by map data.

The floodplain surrounding the present channel shows evidence of former fluvial activity in nearly all areas. Much of this activity can be related to former maps including some channels depicted on Roy's map. Other areas such as at location 1 (figure 3.7b), show a large number of complex sedimentary features. Some of these, such as those marked Br., can be related to former embankment breaches, but others form distinct linear features indicating the presence of former channels. In this reach, which has been stable for at least the last 240 years (as shown by maps 1755 to 1994), the complexity of features indicates that this part of the channel was previously more mobile. Incision and/or confinement by embankments is the likely explanation for its present stability. Similarly, the other two stable sections (sections 2 and 3; figure 3.7c) show evidence of former fluvial activity.

Another use for this data is for the analysis of channel movement. Abandoned channels leave the markings of a complete, if shrunken channel behind, whereas migrating channels will leave a series of parallel marks such as meander scrolls (see section 2.7.). For example, figure 3.7b, feature a, clearly shows an abandoned, infilled channel. The markings at feature b, shows a series of old meander scroll bars. Many of the markings which correspond to channels on the 1863 map are characteristic of abandoned channels. These are often braid arms which have been infilled as another channel becomes more dominant or as channel capacity is decreasing.

Field analysis showed the areas of very low reflectance to consist of silts and sands. Many of these areas corresponded to linear features representing infilled channels. The areas of very high reflectance indicate surface sediments consisting of coarse gravels and these could have been deposited in either of two situations. Firstly, they may have been part of the active river channel as a lateral or medial bar which has since been incorporated into the floodplain. Alternatively, they could have been deposited directly onto the floodplain during extreme flood flows as was observed immediately after the 1990 and 1993 flood events. Therefore, in dealing with areas of very high reflectance, it is important to relate these features to those surrounding them. For example, the presence of formerly breached embankments close by would indicate flood deposited gravels, whereas an area of gravel next to a linear low reflectance feature (an infilled channel) is more likely to be a gravel bar.

The lack of detail in figure 3.7c. is due to the use of aerial photographs for this part of the study reach, rather than the ATM imagery (which shows a greater amount of detail of sedimentary features). It must be noted however, that the accuracy of the rectified photographs is superior to that of the imagery.

3.5. Historically documented floods

The Tay valley has been of great historical importance in Scotland as a routeway through the highlands, and as an area of large settlements such as Perth. Major flood events have, therefore, had significant human impacts and are often well documented. Flood levels (since 1814) in Perth have been recorded on Smeaton's Bridge although they must be treated with some degree of caution as the river here is under tidal influence. Also, some of the earlier floods were caused by ice blockages at the bridge which would have locally elevated flood levels. Table 3.6. gives the dates of the major documented floods.

The earliest recorded flood on the River Tay is that of 1210 when the wooden bridge, the palace and a great part of the town were swept away (Coates, 1916). King William of Scotland lost a son in the flood only barely escaping himself in a small boat (Coates, 1916). The next recorded flood is that of 14th October, 1621 when the newly finished stone bridge at Perth was destroyed. Perth was surrounded by water for 5 to 6 days and many people were made homeless (Coates, 1916). The next two documented floods in Perth were the 1774 flood and the so called, "great flood" of 1814, both of which were accentuated by ice blockages at the bridge which locally elevated the water levels (Coates, 1916).

Table 3.6. Historic flood events of the River Tay.

Date	Level at Smeaton's Br. (m)	Rank	Weather conditions
1210	-	-	Heavy rain and spring tide.
14th Oct 1621	-	-	Heavy rain and south east wind.
Feb 1773	-	-	River Tay frozen, on thawing ice blocked the river at Friarton.
12th Feb 1814	7.0	1	Ice blocked passage of flood waters through arches of Perth Bridge at the end of a severe winter.
7th Oct 1847	6.11	3	Excessive rainfall with a south east wind.
19th Jan 1851	5.65	13	Heavy rain, snow melt, strong westerly gales and a high tide.
20th Jan 1853	5.79	8	Rapid snow melt.
1st Feb 1868	5.90	6	Continuous rainfall, strong westerly winds and snowmelt.
7th Feb 1894	5.64	15	Continuous rain.
31st Jan 1903	5.64	14	Heavy continuous rain, strong westerly gales and snowmelt.
18th Jan 1909	5.52	18	Rapid snow melt, heavy rain.
19th Aug 1910	5.61	16	"unfavourable weather".
21st Dec 1912	5.68	11	Heavy rain, snowmelt and high tides. R.Tay was abnormally high for previous 2 weeks.
9th May 1913	5.66	12	Heavy rain and snowmelt.
22nd Jan 1928	5.77	9	Wettest January on record, snowmelt.
15th June 1931	5.49	19	Heavy rain.
15th Jan 1947	5.55	17	-
17th Feb 1950	6.03	4	Melting snow, heavy rain and high winds.
5th Nov 1951	5.97	5	-
12th Feb 1962	5.73	10	-
31st Jan 1974	5.29	20	Heavy rain throughout January, snowmelt.
7th Feb 1989	5.07	21	-
5th Feb 1990	5.85	7	Heavy rain throughout January, snowmelt.
17th/18th January 1993	6.48	2	Heavy rain, snowmelt.

Records of the flood of October 1847 were the first to describe damage in the study reach. A report in the Perthshire Courier (7th October, 1847) notes that there was "damage from Atholl along the Tummel to the junction of the Tay and from there to Dunkeld". The next flood reported in the Perthshire Courier (1st February, 1868) to have caused damage in this area is that of 1868. The report describes how the railway at the confluence of the Tay and Tummel was flooded to a height of 5'6" and a large part of the embankment was destroyed at this point. Also the railway embankment at Guay was breached. In 1894, another great flood occurred which caused significant damage in the study area. The Perthshire Courier (7th February, 1894) reports that a "lake was formed from Ballinluig to Dalguise" (figure 1.1.). Embankment breaches occurred between Guay and Inchmagrannachan, and at Dalguise, an embankment breach caused the river to run between the road and the railway. Henry Coates visited the area a few days after the flood and in an account of his observations (Coates, 1894) he describes the following scenes:

> *"..in passing up the valley of the Tay from Dunkeld to Ballinluig I had an opportunity of witnessing the enormous amounts of geological work that the river had performed, both in its destructive and its constructive capacity, during its swollen condition. In this section of the valley the flood appears to have done more damage than any spate of recent years, and the results, from the point of view of the proprietor and the farmer, were certainly melancholy. The river had swept over the whole valley floor, breaking down embankments and fences, and carrying away both the vegetation and soil in large quantities. But if the quantity of material carried away was remarkable, the material freshly deposited was still more so. Large areas of ploughed land were completely covered, in some places with layers of sand and*

fine silt several inches in thickness, and in others with beds of gravel and coarse shingle" (page xxii).

On the 31st January 1903, another flood occurred which reached the same height on Smeaton's bridge as that of 1894. Heavy rain and snowmelt were responsible. Again, much damage occurred in the area surrounding the study reach. Coates (1903) reports that between Logierait and Dalguise (figure 1.1.), the Tay broke through its embankments at many points eroding vast quantities of material in some places and piling up new deposits of sand and gravel in others. Grant (1903) gives a very detailed description supplemented by photographs, of the damage caused by this flood. He details embankment breaches just below Tomdachoille on the south bank, two breaches a little further down on the Moulinearn side and the destruction of the retaining wall just below Moulinearn on the opposite side (figure 1.1.). Grant notes that the embanking and confining of the river below Moulinearn has cost the Duke of Atholl "immense sums in the past and that if it were not for the risk of flooding and damage further down the repairs to the banks and protection walls would cause some hesitation". His hesitation indeed got the better of him, for the embankments and retaining wall were never repaired, as a result of which, the Tummel has reverted to a much more natural character. Another breach occurred at the turn in the River at Haugh of Tullymet Farm (40 yards) where a large scoured pool was left, behind which was piled huge amounts of stones and gravel. On the opposite side of the river below Balmacneill House, a large breach occurred at a point that had not previously given way. Heavy silting covered many acres of arable farmland at this point. Other breaches are described near Kindallochan on the north side and near Guay. The rush of water from these breaches carried away the embankment of the Guay Burn. Just below the railway bridge at

Dalguise a gap of over 100 yards was formed with several smaller breaches a few hundred yards lower. Another breach is reported at Dalmarnock which "seldom escapes though a long distance from the river channel" (Grant, 1903).

Figures 3.8a,b and c, are maps showing the location of these documented breaches. Although some of them cannot be located exactly, their approximate positions are marked. The large number of breaches marked for 1903 is mainly due to the extremely good documentation of this flood. A similar number of breaches possibly occurred during the 1868 and 1894 floods, but detailed descriptions are not available.

Other documented floods occurred in 1910, 1912, 1913, 1928, 1931, 1947, 1950, 1951, 1962 and 1974. Although there are no reports of damage sustained in the study area during these events, this does not mean that none occurred. Reports of flood damage mainly centred around the populated areas of Perth.

3.6. Long term climatic trends

Very little work has been carried out on the long term climatic trends in Scotland. However, Smith (1995) has compiled a 236-year time series (1757-1992) of monthly aerial average precipitation for Scotland using the 'official' record compiled by the Meteorological Office (UKMO) from 1869 onwards and extended back to 1757 using previously unpublished data. Figure 3.9a. shows a plot of the annual precipitation over Scotland with the individual annual values in millimetres. However, a better indication of changing trends in precipitation over this period can be gained from figure 3.9b. which shows the ten-year running means of annual precipitation. The cyclical changes between predominantly dryer periods and predominantly wetter periods occur usually every 10-15 years. Table 3.7. gives the approximate dates of the wet-dry cycles. Figure 3.10. also shows the cumulative departures of precipitation from the long-term (1757-1992) mean for periods with three or more consecutive years or seasons above or below the mean.

Table 3.7. Wet and dry periods 1757-1992. (data taken from Smith, 1995).

Wet Periods	Dry Periods
1768 - 1781	1784 - 1794
1794 - 1801	1801 - 1835
1835 - 1845	1856 - 1866
1870 - 1886	1886 - 1900
1901 - 1912	1971 - 1981
1923 - 1940	1940 - 1948
1949 - 1960	1960 - 1982
1982 - present	-

3.7. Discussion

The study reach shows distinctly alternating stable and unstable sections. This has been found to be a characteristic common to many braided rivers (Coleman, 1969; Thorne et al., 1993). Coleman (1969), in a study of the River Brahmaputra, termed unstable reaches as island reaches, and stable reaches, nodes or nodal reaches. Island reaches were found to have large islands with multiple braid bars and tended to have a more changeable planform. The nodal reaches, exhibited a greater stability (Thorne et al., 1993). Thorne et al. (1993) offered no explanation as to why braided rivers tend to exhibit this characteristic. It is difficult at this point in the study, to determine why the study reach shows this distinct pattern, and an examination of the causes of channel change later in this thesis, may provide clarification.

The length of the River Tummel within the study reach, has exhibited instability throughout the historical period, with the exception of a small stable section (section 3) which is naturally confined to the west by bedrock and to the east by maintained embankments. The instability of the rest of the River Tummel within the study reach, may be partly due to the lack of maintained embankments. The Tummel here has moved freely across most of its available floodplain since 1755 and the rest of the floodplain shows sedimentological evidence of channel occupation at some time in the past.

The River Tay from its confluence with the Tummel, to the southern end of the study reach exhibits alternating stable and unstable sections. Much of the Tay along its length here, is confined by embankments which have been continually maintained. The historically documented breaches have been repaired although many have often failed in the same locations during subsequent floods (Gilvear and Winterbottom, 1992).

A study of the sedimentological features on the floodplain shows much evidence of palaeo-fluvial activity throughout the whole of this length of the Tay. This suggests that the sections showing stability from 1755 to present, have not always been stable and that most of the floodplain has undergone reworking at some time in the past.

Channel dimensions have undergone a considerable change throughout the period covered by available OS map data. Roy's map of 1755, depicts a wide channel with a divided planform in the unstable sections of the river. By 1863, the channel is still divided in these sections, but appears to be somewhat narrower and occupying less of the floodplain area. A decrease in active channel area during this intervening period might be expected after the particularly long dry spell experienced between 1801 and 1835, followed by another 10 year dry spell from 1856 to 1866.

Between the period 1863-1899, there was approximately an 8% average decrease in mean channel width in the study reach with only section 4 showing any increase in this parameter. The 1899 OS survey followed a 13 year dry period calculated using the 10 year running means (Smith, 1995). However, in the preceding three years, the cumulative precipitation was 400mm above the long-term mean, with the cumulative winter rainfall for this period, approximately 100% higher (Smith, 1995). A large flood also occurred in 1894 details of which are described in section 3.5. During the 1899 to 1975 period, there was an approximate 27% average decrease in mean channel width, with all sections showing at least a small decrease. The 1975 OS survey was preceded by 4 years of a dry period during which there was a cumulative departure of -550mm from the long-term mean with the cumulative winter rainfall for this period, 70% lower. However, a small winter flood (5.29m at Smeaton's bridge) occurred prior to the 1975 survey.

Much of this decrease in channel width has taken place in the unstable sections. In 1863, these sections were generally wide and multi-threaded (eg. section 6; see figure 3.4f). By 1899, the braid anabranches had decreased in size and were eventually abandoned and infilled so that by 1975 the river had become a narrow single-thread channel. There are three possible conclusions which can be drawn from the dramatic decrease in width during the 1899-1976 period. Firstly, the decrease in width could have been driven by channel incision. This may have occurred as a result of the construction of embankments which confines and accelerates larger flows. This results in bed scouring and channel incision. A depth increase in the channel could mean that channel capacity would remain virtually unchanged with a width decrease. Secondly, it is possible that the 4-year dry period and the 70% decrease in winter rainfall preceding the 1975 survey caused channel width to decrease. The third possibility is that river impoundment at the Pitlochry dam (completed in 1950) could have caused a change in the flow regime, thereby reducing the discharge of channel forming events.

In order to determine which of the above explanations is the most likely, a comparison with 1992 channel dimensions will be helpful. The years prior to 1992 have been extremely wet due to a preceding 12-year wet period. The decade between 1975 and 1985, experienced a cumulative increase in precipitation of 1400mm above the long-term mean. The period between 1985 and 1992 also had a cumulative increase in winter precipitation of 250%. So, if the average channel width in 1992 are comparable with those of 1899, then the preceding years of rainfall before the survey of 1899 were responsible for a large average channel width. The dry period and low winter rainfall prior to 1970 could therefore have been responsible for the dramatic decrease in channel width between 1899 and 1976. If however, the 1992 mean channel width is much less than that of 1899 prior to the river's impoundment, then the channel shrinkage between 1899 and 1976 is most likely due to impoundment or incision.

Apart from the changes in channel dimensions, there are two locations where the river has changed its course by avulsion (figure 3.4a, location 1; figure 3.4b, location 2). Embankment breaches are documented at these locations during the 1903 flood (fig. 3.8a, location a, b and c). These were never repaired and it seems likely that the channel continued to occupy its newly opened channel while the former channel was abandoned and infilled. It is not unreasonable to suppose therefore, that avulsion episodes of this nature would occur more often along the study reach if embankments were not continually maintained and breaches not repaired.

It is difficult to establish whether the documented embankment breaches overlie old river channels as they do not always correspond to channels depicted on Roy's map or the O.S, 1863 map. The floodplain areas around the breaches do show some evidence of former fluvial activity although, so does most of the floodplain. A study of the locations of more recent embankment breaches may provide further evidence.

3.8. Conclusions

1. The study reach of the River Tummel shows marked historical instability with the exception of a short bedrock controlled section (section 3).

2. The length of the River Tay under study, exhibits alternating stable and unstable sections although the reasons for this are unclear at this point in the study.

3. All sections within the study reach including those designated as stable, show signs of previous fluvial activity on the surrounding floodplain.

4. From 1755 onwards channel dimensions have decreased. This decrease is most dramatic during the period 1899-1975. This is either due to incision as a result of embanking, impoundment or climatic fluctuations.

5. Channel avulsions have taken place in two locations and appear to be due to documented embankment breaches in 1903 which were not repaired.

CHAPTER 4

RECENT PLANFORM CHANGE AND THE IMPACT OF FLOODS

4.1. Introduction

The study of recent planform change over an engineering timescale is important for examining the dynamics of river movement which may, subsequently be related to the causative mechanisms. An understanding of the present can also be a key to an understanding of the past; short term changes may provide an insight to the mechanisms of planform change which have occurred over a longer timescale.

In this chapter, recent planform changes are identified by use of aerial photography and analysed using GIS techniques (section 4.2.). A field investigation provides a comparison of methods and accuracy of techniques (section 4.3.). Identified changes are placed in context with flow regimes by an examination of discharge statistics (section 4.4.) and recent flood events (section 4.5.). Section 4.6. concludes the chapter.

4.2. The identification of recent planform changes using GIS

In order to establish recent channel changes over an engineering timescale a different approach is needed from that used to study changes over a geomorphic timescale. In the previous chapter, channel change over the last 250 years was studied using map data. One of the problems of this method is the poor temporal resolution of the data; maps may be updated as infrequently as every 50 years or more which clearly leaves too large a gap to analyse changes occurring over an engineering timescale. Aerial surveys are usually much more frequent than map surveys and this allows the use of a much greater temporal resolution in channel change studies. Surveys by various organisations are carried out typically every 5 to 10 years and are usually available for most areas from the end of World War II onwards. Also, specially commissioned surveys are relatively inexpensive when considering the wealth of data that they can provide.

There are, however, several problems that need to be overcome in the use of aerial photographs. Different surveys will provide photographs at different scales so that a direct comparison of features is not possible without some sort of scale correction procedure. Also, the pitch and roll of the aircraft, caused by turbulence, will introduce an amount of distortion into the photograph which is not present in maps. For example, Werritty and Ferguson (1980) studied channel change on the River Feshie using aerial photographs. A Bausch and Lomb zoom transferscope was used to scale correct the photo's to a 1:10000 base map but the distortions meant that this method still did not achieve an accuracy sufficient for quantitative indices of channel change to be determined. The arrival of GIS with its spatial data rectification methods, has improved the amount and accuracy of data analysis that can be achieved using aerial photographs.

4.2.1. Air photograph availability

The Scottish Office Air Photo' Unit holds photographs from many different surveys carried out in Scotland. An examination of the collection revealed that the surveys which were considered the most useful were those of 7th August, 1968 (1:24000), 6th June, 1971 (1:7500 black and white) and the 18th/24th June, 1988 (1:24000 black and white) all of which produced clear, good quality photographs. Previous surveys were lacking the quality desirable for use with GIS. On inspection of the 1968 and 1971 photographs there were no apparent changes in the river morphology between them, and so the 1971 photographs were chosen for the study as they were of a larger scale.

In addition to these, four aerial surveys of the study reach were carried out by NERC for this research, as a part of their airborne remote sensing campaign. The first survey was on 12th June, 1992 which produced excellent quality false colour infra-red photographs at an approximate scale of 1:5000. The next survey took place on the 31st January 1993 following the extensive flooding of the 17th and 18th of January. Clear, cloud-free, colour photographs at an approximate scale of 1:12000 resulted. Two surveys were flown in the summer of 1994. The first was on the 16th May which due to excessive cloud cover, was repeated on the 13th June. The two sets of black and white photographs were at a scale of 1:5000. The aerial photographs used in this study were those taken of the study reach in 1971, 1988, 1992, 1993 and June 1994.

4.2.2. Conversion of air photograph data to digital data

Two methods are available for the conversion of river channel boundaries as depicted in aerial photographs, into digital format. The first involves scanning the photographs with a digital camera to produce a digital raster image. This is then rectified to a base map using control point information taken from the raster image which is co-registered to a map using a least squares formula. Information from the image may be digitised from the screen as a vector file which is directly overlain onto a base map. One of the problems with this method is that the resolution of the photograph is degraded with conversion to digital format and the definition of control points and channel boundaries will be partially lost. A further degradation of resolution occurs during the image rectification process. This usually leaves the pixels of the transformed image at an angle to the original image and this may only be corrected by resampling. There are three methods for doing this; either by the nearest neighbour in which the digital number (DN) is taken from the nearest pixel; by bilinear interpolation in which the weighted average of the nearest four pixels is taken; or by cubic convolution in which the transfer evaluated weight of the nearest 16 pixels is taken. Whichever method is used the data will be degraded by the process.

The second method involves using a digitising table to digitise the channel outline directly from the photograph. Control point information is also recorded from the photograph and used to rectify the vector file to the base map. The advantage of this method is that the resolution of the original data is not lost and so is used to its best advantage. This was the method used.

One of the problems in determining channel boundaries from aerial photographs, is that of definition. This boundary will vary with different water levels, so a definition of channel boundary that is independent of water levels needs to be determined. The definition used in this study was that of active gravel area. This included all areas which were either open water or consisted of unvegetated gravel. Difficulties will also arise when the channel boundary is obscured by tree canopies. In this event it is most likely that the trees are at the very edge of the channel and the problem can be partially overcome by digitising the line of the channel boundary between one third and one half of the overhanging canopy width.

When all of the photographs were digitised, the control point information for each one was stored in a data file and used for a four point transformation as described in section 3.2.2. which rectified the vector files to the 1:10000 OS base map. This then allowed the information from each year of the photo' dates to be overlain and direct comparisons made between them. Figures 4.1a. to 4.1j. show the 10 sections defined in chapter 3 with the channel positions for each of the 5 photo' dates.

4.2.3. Accuracy assessment

Errors may be introduced into the final data in three ways; boundary interpretation, digitising and data rectification. The latter two factors can be quantified by calculating the root mean square error as described in section 3.2.3. The root mean square error for the rectification of each set of photographs is shown in table 4.1.

Table 4.1. Root mean square errors for rectified aerial photographs.

Year	Root mean Square Error (m).	
	X	Y
1971	4.7	3.9
1988	6.1	5.8
1992	3.9	3.6
1993	5.6	4.3
1994	4.4	5.1

These errors need to be taken into account when using the data for analytical purposes. Gurnell et al. (1994) found errors of similar magnitude in a comparable study with the conclusion that differences in channel boundary positions in excess of 5 metres are likely to be the result of true planform change rather than errors introduced by data handling.

4.2.4. Data Analysis

Once the air photograph information has been input into the GIS, the analysis of the data is much facilitated due to the ease and accuracy of obtaining measurements from the GIS. Six methods of data analysis were used ranging from direct measurements of channel characteristics to more complex analysis using rasterised data. The techniques used are as follows:

1) *Active gravel area:* for each of the ten defined sections, the active gravel area in metres squared was determined for each of the five photo' dates (ie. 1971, 1988, 1992, 1993, 1994).

2) *Channel widths:* for each section, measurements of channel widths were taken at approximately 100 metre intervals along the channel length for each of the photo' dates. This allows variations in channel widths to be plotted against distance downstream giving an indication of relative stability throughout the study reach (figure 4.2.). The average channel width for each section at each date was also calculated the results of which are summarised in figure 4.3..

3) *Sinuosity:* Channel sinuosity as determined by channel length divided by down-valley length, was obtained from each section at each date.

4) *Braiding index:* This was calculated using the equation as defined by Brice (1960);

$$B_I = \frac{2x \text{ total length of bars within reach}}{\text{reach length at mid - channel}} \qquad (4.1.)$$

Only vegetated islands were used to calculate the braiding index so that errors due to differing water levels at the time of the aerial surveys did not affect the results

5) *Multiple polygon overlay:* The vector files for each section and each photo' date were converted into raster files using Laser-Scan's I2Grid package. Each pixel in the raster images represents 5 m^2 on the ground. For each image, areas occupied by the river channel were given a value of one and the pixels representing the surrounding floodplain were given a value of zero. The resulting images for the five different photo' dates were overlain for each section. This resulted in a map in which each pixel has a value representing the cumulative amount of channel

occupancy of that pixel (ie. pixels classified as class 5 have been occupied by the river channel at all of the photo' dates and conversely, pixels classified as class 1 were occupied by the river channel on only one of the photo' dates). The results are summarised in figure 4.4. in which the amount of pixels in each class is calculated as a percentage of the total number of classified pixels in the image for each section.

6) *Simple polygon overlay:* Raster images created from photo's of two consecutive dates, are classified as channel or no-channel and then overlain. A quadtree cell (Gurnell et al., 1994) can then be produced which gives the number of cells eroded or created by deposition in the period between the two photo' dates (see table 2.1.). From this the net amount of erosion or deposition was calculated by subtracting the amount of pixels created by deposition from the number of pixels eroded and multiplying the result by 25 (the area of a pixel in m^2). The net erosion or deposition that has taken place between two photo' dates was calculated as a percentage of the area of the earlier of the two photo' dates. These results are summarised in figure 4.5. A summary of these analyses for individual sections are presented in figures 4.6a. to 4.6j.

4.2.5. Discussion

Figures 4.1a to 4.1j show the overlays of the air-photo' data which allow the determination of which areas of the sections have experienced the greatest amounts of change. These areas have been located and their positions are shown on figures 4.1a to 4.1j and are marked by the letters A to L. The details of changes which have occurred at these locations have been interpreted using the information from the diagrams and also from the aerial photographs themselves. The details for each labelled zone are outlined below.

A. The western arm of the channel in 1971 at this location, became cut-off between 1971 and 1988 and the meander bend just upstream of this extended to its present position where it is now prevented from further movement by rip-rap. An area of bare gravel developed just north of this cut-off arm and has extended in a southerly direction following the path of an abandoned channel which can be seen on the 1863 map (see figure 3.4a).

B. Following the cut-off of the western arm between 1971 and 1988, the eastern channel became enlarged. The enlargement of this zone continued progressively between 1988 and 1993, with erosion of the western bank. Between 1993 and 1994 however, there was no more erosion of this bank and a large area of the gravel bar on the opposite side has become vegetated and stabilised.

C. Enlargement of the active gravel area at this zone is occurring by the extension of bare gravels in a southerly direction. This follows the path of a former river course the abandonment of which occurred subsequent to the 1903 flood (see figure 3.4b). Just to the north of this expanding gravel area the eastern bank has been eroding rapidly since 1988 which is coupled with a small but expanding mid-channel bar situated near the bank on the eastern side.

D. At this zone, 10 to 15 metres of bank erosion has taken place between 1993 and 1994 on the eastern bank which had previously been stable since at least 1971. The build up and stabilisation of gravels on the opposite side may be a contributory factor.

E. A lateral gravel bar which was on the western side of the channel in 1971 was dissected by the channel and became a medial bar by 1988. The channel enlarged on the western side of this bar and a large part of the western bank at this location has been eroded between 1988 and 1993. Most of that erosion took place between 1988 and 1992 with a smaller amount having occurred between 1992 and 1993. No further retreat appears to have taken place between 1993 and 1994. Contemporaneous with this erosion, was the development of the gravel bar which is now attached to the eastern side of the channel. This has undergone accretion and extension since 1988 and parts of it became vegetated and stabilised by 1994. It is likely that the growth of this bar has been the driving mechanism for the associated erosion on the opposite bank.

F. Small amounts of progressive erosion have been occurring at this location since 1988. It is possible that channel embayment at location E may have re-directed the channel thalweg towards the eastern bank at this point thus increasing the shear stress on the outer bank.

G. The channel at this location has undergone a large amount of expansion which mostly occurred between 1988 and 1992 with a smaller amount occurring between 1992 and 1993. Several small medial bars formed within the channel during this period, one of which on the eastern side of the channel, became vegetated and stabilised between 1993 and 1994 reducing the active gravel area. Figure 3.4d. shows this location to be an extremely wide channel in 1863 and 1899 which underwent a large reduction in size between 1899 and the channel as depicted on the 1975 map.

H. The eastern bank at this location, which was a formerly stabilised lateral gravel bar, retreated between 1988 to 1992. Further erosion occurred between 1992 and 1993 but subsequent deposition and vegetation colonisation between 1993 and 1994 returned the limit of active gravel area to the 1992 position.

I. The variability in active gravel width at this location is due to the frequent deposition of fresh gravels on the gravel bar situated here. These are subsequently vegetated and stabilised. This illustrates the difficulties in the definition of active channel used in this study as areas of channel which are either water or unvegetated gravel. High magnitude events will cover vegetated areas with newly deposited gravel but these cannot really be considered as active parts of the channel. This problem is difficult to resolve so changes in active gravel area must be treated with a degree of caution and supplemented by field observations.

J. The variability in channel width at this location is occurring for similar reasons as that at location I. A lateral gravel bar on the eastern side has undergone several phases of gravel deposition and subsequent recolonisation by vegetation.

K. A wide, divided channel characterised this section in 1971. However, by 1988 the channel had abandoned its eastern arm and become a relatively narrow stable channel and has remained stable to date.

A discussion of results determined by the data analysis techniques used (section 4.2.4.; 1 to 6) is given below.

1. Active gravel area: Figures 4.6 a to j, (v) show the changes in active gravel area that have occurred between 1971 and 1994. Between 1971 and 1988 the active gravel area of

nearly all the sections decreased or remained the same. The periods 1988 to 1992 and 1993 to 1994, both show increases in active gravel area for most of the sections. Between 1993 and 1994 however, the majority of the sections showed a decrease in active gravel area.

2. Channel widths: Figure 4.2. shows the changes in channel width along the study reach. It is difficult to discern any clear trends from this diagram although it can be seen that some parts of the study reach show more variability in width over time, than others. Figure 4.3. which is a graph of average channel widths for each section is a clearer summary of this data. There appears to be a certain periodicity in this data extending over two to three sections. Sections 1, 4, 5 and 6 generally exhibit greater average widths than sections 2, 3, 7, 8 and 9. Section 7 has a large average width in 1971 but has since become narrower. Variability in channel widths over time, appears to be greater in the sections with wider channels.

3. Sinuosity: (see figures 4.6 a to j (vi)). There are no discernible trends in changes in sinuosity over time for the 10 sections. This is most likely due to the fact that this is a wandering gravel-bed river as opposed to a meandering one. In addition, measurable changes in sinuosity would be expected to occur over a much longer time period.

4. Braiding index: (see figures 4.6 a to j (vi)). Again, as with sinuosity, no trends are discernible in the data. The definition of islands within the study reach however, is somewhat dubious for measurements of this sort, as only vegetated island could be used to avoid changes in water levels affecting the results.

5. Multiple polygon overlay: (see figures 4.4. and 4.6a to j (i), (iii)). The results of this analysis are summarised in figure 4.4. which shows the percentage number of pixels classified into each channel occupancy class for sections 1 to 10. Sections with the lowest percentage of pixels in class 5 will be those which have shown the most movement across the floodplain. Section 1 has the lowest percentage of pixels in this class (41%) closely followed by section 10 (48%). Both of these sections underwent a major shift in channel position which occurred during the 1971 to 1988 period. Sections 3, 5, 7 and 9 which were classified as stable using the historical map analysis carried out in chapter 3, all show a greater percentage of class 5 pixels in comparison to the other sections which were classified as unstable. This demonstrates the continuation of a higher degree of stability of these sections in comparison to the other sections.

6. Simple polygon overlay: (see figures 4.5. and 4.6a. to j. (iv)) The results of the simple polygon overlay data analysis method are presented in figure 4.5. which shows the percentage area eroded or created by deposition in the four intervening periods between the five photo' dates. In the period 1971 to 1988, 8 out of 10 sections exhibited a net deposition (7.1% average for the 8 sections) but the interval between 1988 to 1992 showed a net erosion in 8 out of the 10 sections (6.8% average for the 8 sections). During the period 1992 to 1993 9 out of 10 sections experienced erosion (5.2% average erosion for the 9 sections) and 7 out of 10 sections showed net deposition during 1993 to 1994 (5.2% average over the 7 sections). In order to determine which sections underwent the most change throughout the 1971 to 1994 period, the percentage amounts of erosion and deposition were totalled to give an index of total change. The results are shown in table 4.2.

The five sections that ranked the highest in the analysis of total percentage change throughout the period are 1, 10, 5, 6 and 4 which correspond to the sections which have the larger average widths as shown on figure 4.3.. All of these sections are classified as unstable with the exception of section 5. The high amount of change in sections 1 and 10 is mostly due to the fact that both have experienced channel avulsion. Sections 3 and 9 show the least amount of change during this period and so can be considered as being the most stable.

Table 4.2. Total amount of change in sections 1 to 10 (1971 to 1994).

Section Number.	Total percentage change.	Rank.	Stable (S) or Unstable (U).
1	42.8	1	U
2	23.4	6	U
3	15.3	9	S
4	27.7	5	U
5	37	3	S
6	28.9	4	U
7	20.2	7	S
8	18.2	8	U
9	10.8	10	S
10	42	2	U

4.3. The identification of channel changes by fieldwork

In addition to the investigation of river channel changes within the study reach by use of aerial photographs, a field based study was also undertaken. Four sites were identified as appearing prone to channel change. All sites exhibited steep banks with overhanging or slumped vegetation which is usually indicative of active erosion. The sites were studied using field techniques for two main reasons; firstly, in order to establish what level of detail can be gained from field study in comparison to using more remote methods, and to provide "ground truth" data with which to assess the accuracy of the other methods used in this study. Secondly, the field sites were studied in order to determine the active mechanisms of bank erosion and to try and establish the causative variables influencing bank erosion. The four sites that were chosen are identified on figure 4.7. and are all situated on the River Tummel.

4.3.1. Description of field sites

Site 1. (Tomdachoille Island; plate 4.1. and figure 4.7.) consists of a steep undercut western bank opposite a large, mainly unvegetated gravel bar on the eastern side. The bank of the western side is a composed of sandy-silts underlain with non-cohesive gravels with a sandy matrix. The top of the bank and the proximal floodplain area, are vegetated with unimproved, rough grassland. Tomdachoille Island forms part of the designated SSSI known as the Shingle Islands. Remnants of old embankments can be seen but these have been breached many times and no longer follow the course of the present day river.

Site 2 (Moulinearn north; plate 4.2. and figure 4.7.), is also composed of layered sandy-silts and coarse gravels. Figure 4.8. is a schematic diagram of the bank showing the distribution of sediments. At the upstream end of the monitored site, the sediments are mainly layered sandy-silts with thin bands of relatively fine gravels. Towards the downstream end of the eroding bank however, the silts give way to coarse gravels and cobbles which are loosely packed with only a small amount of finer sediment matrix. The base of the river bank is protected by a large gently sloping "slump zone" consisting of coarse gravels and cobbles. Mechanisms of erosion appear to be different at the two ends of the site. At the upstream end, large blocks of fallen river bank are evident. Towards the downstream end however, lumps of turf can be seen at the bottom of the bank and also, the turf is overhanging at the top of the bank. This suggests that the bank sediments here are being entrained directly by the current at high flows causing the overlying vegetation to be undercut. The riparian zone of the floodplain at this location, is vegetated with rough grasses used for grazing.

Site 3 (Moulinearn south; plate 4.3. and figure 4.7.) is a steep river bank consisting entirely of laminated, cohesive sandy-silts. Some evidence of fallen blocks can be seen as at the upstream end of site 2. The erosion mechanism appears to also be by block failure at this location. The riparian zone is vegetated by rough grazing.

Site 4 (Ballinluig Island 4.4.) also forms part of the Shingle Islands SSSI. The river bank here is steep with very little protection at the base from a "slump zone". It consists entirely of unconsolidated, coarse gravels and cobbles overlain by a thin (<50cm) layer of soil. The riparian zone is vegetated with natural woodland of Birch, Alder and Scots Pine. Evidence of active erosion is given by the fallen trees at the banks edge. At this location it is most likely that the bank sediments are being entrained directly into the flow undercutting the root zone of the overlying trees. The destabilised trees are then slumping forward dragging large parts of the river bank and soil layer with them.

4.3.2. Field techniques

The field investigation was mainly involved in examining the rate and distribution of river bank erosion. One of the most widely used methods for this type of investigation is the placement of erosion pins which are inserted at right angles into the river bank so that they are flush with the edge. Erosion rates are determined by measuring the progressive amount of exposure of the pins over the period of study. It was decided however, that due to the size and dynamic nature of the River Tummel, erosion pins would be insufficient to measure amounts of erosion that may take place. An alternative method was decided upon, in which a series of markers were placed parallel to the bank edge but set back at a distance of around 10 metres. The pegs were also set apart at 10 metre intervals. Measurements were repeatedly taken from these fixed markers to the bank edge in order to give an indication of erosion rates.

The second method of field investigation was accurate surveying through the use of electronic distance measurers (EDM). These work by sending a beam of infra red light to a reflector. The time taken for the beam to return allows the calculation of the distance between the EDM and the reflector. By also knowing the vertical and horizontal angle of the beams path it is possible to determine the exact position of the reflector and the height difference between it and the EDM. The distance and angle measurements are stored electronically during the survey and can later be downloaded into a geographical CAD package where the calculations are made and a map produced. Two full surveys of the three sites were carried out; one in August, 1992 using a Sokkisha SDR-2 EDM and the other in June, 1993 using a Leica EDM. The results from both surveys were downloaded and processed using LISCAD plus. For ease of processing and comparison with map data, the survey maps were converted into Laser-Scan's IFF file format. The two sets of survey data for each site were superimposed so that a direct comparison could be made. The position of the marker pegs were used as control points for a two point transformation of one of the sets of data. A two point transformation uses a least squares fit of the sets of co-ordinates to compute the transformation:

$$X=a1+a2*x-a3*y \tag{4.1.}$$

$$Y=a4+a3*x+a2*y \tag{4.2.}$$

This type of transformation will only correct for rotation, scaling and absolute position and does not change the relative position of the points within the file being rectified. In this case as the scales of the two surveys are the same, the rectification will just correct for rotation and absolute position.

4.3.3. Results

Figure 4.9., 4.10., 4.11. and 4.12. show the results of the two surveys for each site and also show the positions of the marker pegs. The bank markers were emplaced in June 1992. Remeasurement of the sites in December, 1992 found no change to have taken place. However, subsequent to the major flood event of January, 1993, large lengths of the bank had been eroded. Table 4.3. shows the amount of erosion measured which was caused by the January, 1993 flood event at site 1, 2 and 3 (Tomdachoille Island and Moulinearn north and south) although at site 2 about more than half of the marker pegs had been eroded away.

A thick covering of sand and the large amount of flood debris caught in the vegetation at site 4 (Ballinluig Island) had covered most of the markers and remeasurement was not possible.

Table 4.3. Erosion measured from field sites as a result of the 1993 flood event.

Tomdachoille Island		Moulinearn (north)		Moulinearn (south)	
Peg Number	Erosion (metres)	Peg Number	Erosion (metres)	Peg Number	Erosion (metres)
F1	2.02	F1	4.17	F1	0.15
F2	1.37	F2	5.29	F2	0.33
F3	2.63	F3	5.75	F3	0.23
F4	2.64	F4	6.61	F4	1.29
F5	3.60	F5	6.96	F5	1.90
F6	5.56	F6	8.69	F6	1.78
F7	6.12	F7	8.79	F7	1.13
F8	6.20	F8	peg missing approx. 10.30	F8	1.78
F9	6.52	F9	peg missing approx. 12.00	F9	2.35
F10	7.05	F10	peg missing approx. 12.70	F10	1.28
F11	7.14	F11	peg missing approx. 12.80	F11	1.06
F12	8.40	F12	peg missing approx. 12.50	F12	1.18
F13	8.97	F13	peg missing approx. 12.50	F13	1.62
F14	Peg missing	*	*	F14	1.43
*	*	*	*	F15	0.92
*	*	*	*	F16	1.23
*	*	*	*	F17	1.28
*	*	*	*	F18	1.75
*	*	*	*	F19	2.09
*	*	*	*	F20	2.79

4.3.4. Discussion

All the sites, except site 3, exhibited large amounts of bank erosion during the January 1993 flood event. Site 2 experienced the most erosion and this was greatest at the downstream end of the site. This area of the bank had the highest proportion of unconsolidated gravels and cobbles. The erosion mechanism here was unusual in that the bank had not been undercut. During the flood, the main flow of water had been over and across the bank at an angle. This had the effect of "peeling back" the overlying turf and exposing the bare gravels underneath. These were then transported away by direct entrainment from the flow.

Tomdachoille and Ballinluig Islands both experienced similar erosion patterns. The two western banks at these sites have a concave curvature with the thalweg directly adjacent to the bank. Both sites exhibited an increasing amount of erosion towards their downstream ends. Undercutting of the unconsolidated sediments and subsequent slumping of overlying soils and vegetation, was the dominant mechanism active at these locations.

Site 3 exhibited very little erosion. This is probably due to the fact that it consists entirely of cohesive sandy-silts which would be expected to show a greater degree of stability than composite or non-cohesive bank sediments. However, between February, 1993 and June, 1994 the bank at this site experienced a more rapid retreat to the order of 10 metres or more. It was not possible to measure this in the field as the marker pegs had been destroyed and could not be used for reference. The erosion however, is evident from the aerial photograph survey and a visual inspection of the site found this to be the case. Many large failed blocks were also present at the base of the bank. Failure of this type is common in cohesive banks where the motivating force is the down-slope component of the weight of the potential failure block (Hooke, 1979; Thorne, 1982). Mass failures of this type occur following rather than during high flows in the channel. This is probably because the switch from submerged to saturated conditions that occur during a lowering of water levels increases considerably the weight of the river bank material which will in turn increase the chance of failure (Thorne, 1982).

The large amount of erosion that occurred during the flood event of January, 1993 was unexpected. When the marker pegs were emplaced it was thought that it would be sufficient to set them back 10 metres from the river bank in order to monitor erosion. The fact that pegs were missing at all the sites and also covered by sediment at site 3 shows the limitations of using this method for monitoring erosion in actively eroding channels. The method is also relatively labour intensive and only a small spatial area could be monitored as it was not possible to emplace more pegs due to obstacles or conflicting land use. Figures 4.9., 4.10., 4.11. and 4.12. highlight the small spatial coverage obtained by this method in comparison to the EDM surveys.

The EDM surveys, however, allow a greater spatial coverage and also direct, accurate visualisation of the changes between survey dates. One of the problems with surveying however is that it relies on direct visual contact between the surveying instrument and the reflector and in wooded areas or rough terrain as is common in natural riverine environments, this is not always possible. This still restricts simple surveys to relatively small spatial areas unless the instrument is repeatedly moved and common reference points can be obtained. This increases the survey time considerably and is not always feasible in inaccessible areas. As can be seen from figures 4.9., 4.10., 4.11. and 4.12. the extent of the survey is still insufficient for a full picture of river bank erosion distribution to be obtained. The acetate overlays on figures 4.9., 4.10., 4.11. and 4.12. demonstrate the accuracy achieved by the aerial photograph survey in comparison to the field survey. At site 1, the bank positions for the field and aerial surveys match extremely well. At site 2 however the match is less accurate with the amount of erosion evident in the air-survey underestimated. It appears that the 1993 aerial photograph has been rectified relatively accurately in this area but the 1992 aerial photographs show the bank line about 10 meters further back than it should be. The differences in extent of the gravel bars is most likely to be a result of differing water levels as the 1993 aerial photographs were taken at a time of very high discharge. One of the reasons for the poor rectification of the 1992 photo's in this area is the lack of ground control points available to use in the data transformation. The 1993 photo's appear to be a more reliable representation of the channel planform which is probably due to a lesser degree of distortion. Site 3 and 4, as in site 2 show a high degree of accuracy in comparing the information taken from the rectified air-photo's with the field survey data.

4.4. Rainfall and discharge records

There is a general consensus of opinion in the literature that Northern Britain has become progressively wetter since the 1980s. Gregory et al. (1991) using a composite rainfall series for Great Britain, showed that Scotland was at least 5% wetter in the 1980s than in any decade since the 1930s. The step-up in the series from a mean aerial rainfall of 1270mm in the 1970s which was a very dry decade to a value of 1445mm in the 1980s is an increase of nearly 14%. Marsh and Monkhouse (1990) state that the 1980s was the wettest decade on record. Figure 3.9b. taken from Smith (1995) shows the 10 year running means of precipitation and demonstrates the extent of this increase.

This increase in precipitation is reflected in data derived from discharge measurements. Figure 4.13. shows the 5 year running average discharge based on the monthly means for Caputh which is downstream of the study reach on the River Tay. This demonstrates that the average discharge has increased at a steady rate between 1970 and 1988. Figure 4.14. shows the 3 year running average discharge for Port-na-Craig on the River Tummel. Here, an increase between 1973 and 1992 is also evident. However, if the data is split up into the seasonal means as in figure 4.15., a better analysis of trends can be seen. The 3 year running mean for the average winter discharge (DJF) is relatively low between 1977 and 1982 and also between 1987 and 1989. In 1990 the mean increases sharply again. The spring (MAM) and autumn averages are in keeping with the overall mean in that they both increase gradually between 1973 and 1992. The summer mean remains relatively unchanged throughout the period.

Figure 4.16a. examines the flood frequencies and magnitudes between 1952 and 1993. The graph was compiled from POT (peak over threshold) data for the Caputh gauging station with a threshold of 700 m^3s^{-1} and this resulted in the selection of 66 events over the 41 year period (data supplied by H. Grew, Geography Department, St. Andrews University). There is an apparent increase of events of lower magnitude (800 to 900 m^3s^{-1}) that has occurred since 1974. This is in keeping with the mean seasonal discharge analysis. A higher number of events of a lower magnitude would be expected with an increase in flows during the spring and autumn seasons. It is difficult to decipher any apparent trends in floods of a higher magnitude with such a short period of accurate records. In an examination of the longer term distribution of recorded major flood events as measured at Smeaton's Bridge in Perth (figure 4.16b.), there is a marked reduction in high magnitude events between 1962 and 1990. The 1990 event in the context of long term data is not particularly exceptional. The 1993 event however, is second only to that of 1814 but it is impossible to determine any pattern of changing frequencies of floods of this size with records only extending back 200 years. It appears though, that apart from the 1993 event, there is no significant increase in floods of high magnitude. This is supported by research carried out by Arnell et al. (1990), who in a study of the impact of climate variability on river flow regimes in the UK found no conclusive evidence that the period 1969 to 1988 showed any significant increase in the frequency of high magnitude events.

4.5. The 1990 and 1993 flood events

It is evident from the field and aerial photograph studies, that most of the observed channel changes that occurred during the study period happened during the two major flood events of 1990 and 1993. The hydrology and effects of these floods are examined in this section.

Persistent and widespread rainfall throughout January, 1990 which was almost twice the long term average, saturated the Tay catchment causing high river flows and filling many of the reservoirs. Much of the continued precipitation that occurred on the 1st and 2nd of February fell as snow on the higher ground and remained until the sudden increase in temperature on the 3rd and 4th of February. Further heavy rainfall on the 4th coupled with a rapid thaw produced an exceptionally high run-off which resulted in extreme flows in the Rivers Garry, Tummel, Tay and Earn. The peak flow at Port-na-Craig on the Tummel of 970 m^3s^{-1} occurred at 1.30 am on the 4th February. Flood flows persisted from 7am on the 4th January to 12 midday on the 8th January; a total of 101 hours. The flood at Caputh lasted from 6am on the 4th February to 12 midday on the 8th February (102 hours) with the peak of 745m^3s^{-1} occurring at 7.15 am on the 5th (TRPB 1993).

The month of January, 1993 was one of exceptional weather conditions. On 11th of January strong winds and heavy snow showers caused drifting of snow over the Central Highlands and eastern Scotland. Conditions persisted until the 13th by which time repeated snowfalls had led to an accumulation of large amounts of snow which extended to low lying areas. During the day of the 14th of January a slow thaw began which accelerated overnight as temperatures rose to 4/5°C and heavy rainfall began. The thaw continued but large amounts of snow still lay on higher ground until the 16th when further heavy rainfall and a rise in temperature to 10 to 12^{0}C caused a more rapid and extensive thaw. Rivers, already high from the previous day, quickly rose to extreme levels. The peak flow of 1048 m^3s^{-1}, at Port-na-Craig at 5.15am on the 17th of January, was 3 times the natural channel capacity in the downstream end of the study reach (TRPB, 1993). At Caputh the peak flow of 1874 m^3s^{-1} was recorded at 10.45 am on the 17th of January (TRPB, 1993).

A comparison of the hydrographs (figures 4.17a. and 4.17b.) for these two floods highlights their different nature. The 1990 event began with high flows with water levels rising steadily and falling slowly after the peak giving a relatively broad hydrograph. The 1993 event was more "flashy" in that the rising limb is steep culminating in a sharp peak with a steep recession limb. The 1990 flood had a smaller peak discharge than the 1993 flood but was sustained for a much longer period.

The study reach suffered extensive flooding during both these events with many embankment breaches. These were mapped by Babtie, Shaw and Morton Consulting Engineers, for the 1990 flood, and by aerial photograph interpretation in 1993 by the author of this thesis. Considerable erosion of agricultural land and extensive deposition of sand and gravels also occurred on the floodplain area. Figures 4.18a, b and c, show the location of flood embankment failures that occurred during the 1990 and 1993 flood events. These diagrams show that the breaches in 1990 and 1993 occurred in very similar locations and highlight the particular stretches of embankments that are vulnerable. Most of these have been built at an angle to the main down-valley direction. Location A, which is a redundant channel at normal flow levels, is obviously reoccupied at higher flows. The sharp angle of turn in embankment direction has caused it to be susceptible to breaching. This situation is the same at locations B and C which are both located on bends of abandoned channels. Location D and E are embankments which both lie on the outside bends of sharp turns in the river.

Along the study reach, there were many more embankment breaches during the 1990 flood than in 1993. This is explained by the longer duration of the 1990 flood, which caused a more lengthy, sustained attack of the embankments by high water levels.

4.6. Conclusions

1. Unstable sections have the lowest percentages of class 5 occupancy and are therefore, still the more unstable sections of the study reach.

2. The stable sections have a higher percentage of class 5 occupancy and can still be considered as stable.

3. The sections which have experienced the greatest percentage of change are those with the largest average widths.

4. Between 1971 and 1988, the study reach experienced an average 7.1% reduction in active gravel area through deposition and stabilisation of gravel bars. This coincided with an increase in rainfall and overall mean annual discharge as well as an increase in small flood events. However, no major flood events occurred during this period.

5. Between 1988 and 1992 an average expansion of 6.8% in active gravel area occurred. Two large floods occurred in this intervening period. One, of 1168 m^3s^{-1} (Caputh) in February 1989, and one, of 1747 m^3s^{-1} (Caputh) in February 1990, which was a lengthy, sustained flood lasting 102 hours.

6. Between 1992 and 1993 an average of 5.2% expansion in gravel area occurred along the study reach, which as demonstrated in the field, occurred almost entirely during the flood

event. The lesser amount of erosion that occurred during this period compared to the previous one could have been due to the more prolonged flooding in 1990.

7. Rapid recovery of channel dimensions occurred between 1993 and 1994 when an average reduction of 5.2% in active gravel area occurred by vegetation recolonisation of gravel deposits.

8. It follows that most of the increases in channel dimensions in the study reach, occur as a result of major flood events and their absence allows a marked reduction in active gravel area as occurred between 1971 and 1988. Events of smaller magnitude (less than 1000 m^3s^{-1} at Caputh) seem to cause little bank erosion.

9. Erosion due to high magnitude events was greatest at river banks consisting of composite or unconsolidated sediments. This was accompanied by the expansion of medial or lateral gravel bars opposite the site of erosion.

10. Banks consisting of consolidated finer grained sediments remained more stable during flood flows but underwent a greater amount of erosion during subsequent floods of lower magnitude. This is thought to be due to the greater cohesion of these sediments and thus resistance to fluvial erosion. Erosion of these types of sediments is more often related to wetting and drying episodes than fluvial events.

11. The more recently abandoned channels became reoccupied during flood flows as demonstrated by the extension of bare gravels from the present water course in a direction following these former courses.

12. The use of aerial photographs in conjunction with GIS rectification techniques provides high quality, reasonably accurate data on a wide spatial scale allowing detailed analysis of river channel changes.

CHAPTER 5

THE QUANTIFICATION AND EFFECTS OF IN-CHANNEL MORPHOLOGY

5.1. Introduction

The study of river channel planform is important for the investigation of morphological change. It is however, only a part of the whole picture as it is restricted to two dimensions. In order to achieve a more complete representation of channel morphology it is necessary to incorporate the third dimension so that the effects of channel bedform can be explored. This information is traditionally obtained by taking cross-sections of the river and extrapolating the data between these. However, difficulties arise when applying this method to large rivers. It is also time-consuming as well as spatially restrictive thus requiring a large numbers of cross-sections to gain morphological detail. Moreover, retrospective changes are difficult to obtain as is possible with planform studies by the examination of old maps and aerial photographs.

This chapter examines the theoretical background of bathymetric mapping using remotely sensed data (section 5.2.) and a preliminary field investigation is reported in section 5.3. The application of the method is described for ATM data in section 5.4. and to black and white aerial photography in section 5.5.+ Section 5.6. details the morphology of the study reach and section 5.7. concludes the chapter.

5.2. Theoretical background of bathymetric mapping by remote sensing methods

Bathymetric mapping using remotely sensed data is not an entirely new idea. It has been widely used in the past for mapping bottom topography within coastal and estuarine waters (Polcyn et al., 1970; Polcyn and Lyzenga, 1979; Cracknell et al., 1982). More recently, studies of this sort have included those carried out in the fluvial environment. Lyon et al. (1992) used airborne multispectral scanner data for mapping bottom sediment types and water depths in the St. Marys River, Michigan. Hardy et al. (1994) acquired multispectral videography of the Green River, Utah, which was used to classify relative water depths and mesoscale hydraulic features.

The technique relies on there being a correlation between reflectance levels as observed in the multispectral imagery or aerial photographs, and water depth. Bouger's Law states that in an absorbing medium, the intensity of radiation decreases exponentially with distance. Therefore the level of light reflected from a uniform bottom of a body of water will not be linearly related to water depth. Lyzenga (1981) proposed an algorithm which can be applied to observed reflectances so that they become a linear function of depth:

$$X_i = \ln (L_i - L_{w(i)}) \qquad (5.1)$$

where X_i is the variable that is linearly related to water depth in band i, L_i is the observed brightness and $L_{w(i)}$ is the deep water reflectance in the same band (ie. the reflectance levels from water deeper than that which light can penetrate).

There are three other factors apart from water depth however, which affect reflected light levels from a water body:

1. water surface backscatter,
2. water turbidity and colour,
3. substrate reflectance.

Water surface backscatter can occur for two reasons. Firstly, if the angle of the camera is such that sun glint is reflected off the water surface and secondly, water surface backscatter can also occur in areas of high turbulence. Hardy et al. (1994) found in their study that the presence of high surface turbulence precluded any delineation of depth features due to the surface dominated reflectance and it was mapped as a separate category in their classification.

Water turbidity causes an increase in reflectance levels from the water body and also drastically decreases the maximum water depth of penetration by light. In areas of high turbidity bathymetric mapping is, if possible at all, highly problematic and in these circumstances it is probably better to find other methods for bathymetric mapping.

The influence of bottom reflectance on water body radiance is a more complex problem. Lyzenga (1981) describes a procedure for using multispectral data to detect differences in bottom reflectance over areas of variable water depth. This technique relies on the fact that the bottom-reflected radiance is a linear function of bottom reflectance and an exponential function of water depth. By using two bands of different wavelengths from the multispectral data, equation 5.1. can be applied to the data in order to derive variables x_i (the variable that is linearly related to water depth in band i) and x_j (the variable that is linearly related to water depth in band j). If x_i is plotted against x_j and the water depth is varied, then the data points will fall on a straight line. If the bottom reflectance is changed, the data points will fall along a parallel line which is displaced from the first. Thus by measuring the amount of this displacement, a change in bottom reflectance can be detected.

5.3. Preliminary field investigation

In order to examine the effects of different water depths on the reflectance levels of light, a portable spectroradiometer (Spectron SE590) was borrowed from the NERC equipment pool in order to take measurements in the field. The instrument records light radiance in the spectrum 400 to 1100 nm using a down-looking sensor head. An up-looking cosine receptor with diffuser, records incoming radiance spectra which is used to calibrate data recorded by the down-looking sensor against incoming light levels. A white reference panel is also used to take frequent measurements with the down-looking sensor to provide regular instrument calibration throughout the period of data recording. The data is recorded by a CE500 controller on cassette and can be downloaded directly to a PC (Milne et al., undated). The data can then be processed and calibrated using NERC's Spectron SE590 processing software. Reflectance levels are calibrated, calculated and can be plotted in graph form against the recorded spectra range.

Several spectral recordings were taken on the Moulinearn stretch of the River Tummel, at locations of different water depths. The instrument was held at 1 metre above the water surface and readings were taken at increasing water depths of 10cm intervals in an area with a slight algal covering on coarse gravel bottom sediments. The maximum depth at which recordings were taken was 60cm, as at depths greater than this, it proved too difficult to hold the instrument safely and high enough above the water surface.

The spectroradiometer was also used to examine the effects of different bottom types on spectral reflectance values. Readings from four different locations were taken; two from an area of clean gravels at depths of 20 and 30cm, and another two at 20 and 30cm, in an area which had bottom gravels with a thick algal covering. Many more readings were taken in areas with different degrees of algal covering at different depths, but the weather at the time of these extra readings was overcast with variable amounts of cloud cover on the day. The restricted period of equipment loan prevented further experimentation.

5.3.1. Results of field investigation

Figure 5.1. shows the spectral reflectance levels obtained for differing water depths. It can be seen that on uniform bottom sediments, water depths can very clearly be distinguished between 600 to 800 nm (0.6 to 0.8 μm). Figure 5.2. shows the results of the survey over areas of different bottom reflectance. At wavelengths between 600 and 700nm the effects of absorption in this part of the spectra by algal covering on the bottom sediments, completely outweigh the effects of water depth and the reflectance levels for 20 and 30 cm depth are the same at these wavelengths. Between 700 and 800nm however, although the algal covering causes some amount of absorption in this part of the spectra, it is still possible to determine difference in the water depths.

5.3.2. Discussion of field results

In terms of water depth, Daedalus ATM bands 4 (0.605 to 0.625μm), 5 (0.63 to 0.69μm) and 6 (0.695 to 0.75μm) all lie within the 600 to 800 nm range and so would be expected to give good correlation's between reflectance levels and water depths for this particular reach. The results of the study on bottom reflectance show that between 600 and 700nm, the influence of water depth may be outweighed in areas with large amounts of algal covering. It would be expected therefore, that the best results for water depth determination would be obtained by using the wavelengths 700 to 800nm.

However, the lack of data regarding the effects of bottom reflectance mean that the results are not totally conclusive. Nevertheless, the limited results obtained, show that ATM band 6 (0.695 to 0.75μm) is more likely to give accurate results in a correlation of water depth against reflectance values in an area with high amounts of algal covering on the sediments.

5.4. Bathymetric mapping using multispectral imagery

Using the theory outlined in section 5.2., the use of multispectral imagery for the purposes of bathymetric mapping was examined.

5.4.1. Data acquisition and methods

During the acquisition of the ATM multispectral imagery in 1992, several cross-sections of the River Tummel were surveyed. This resulted in 184 depth measurements which were taken simultaneously with the imagery thus providing ground-truth data. Marker boards (2 metre x 2 metre white boards) were also placed at fixed positions on the ground so that the positions of the cross-sections could be located on the imagery. Water samples were also taken to quantify water turbidity at the time of the aerial survey.

The digital data was analysed using the IDRISI raster based GIS software. Bands 9 to 12 were not used, as depth of light penetration in water at these wavelengths is limited. In order to identify the deep water reflectance, the land areas were 'masked' by digitising around the land/water boundary and creating polygons which overlay the land and isolated the river. A histogram of the resulting image allowed the examination of the range of digital numbers which were reflected from the river. The image used, encompasses areas of deep water beyond which light will no longer be reflected and therefore the lowest digital number on the image histogram for each band will correspond to the deepest areas of water and can be used for the deep water reflectance values.

The pixels corresponding to the locations of the 184 depth measurements were identified and the digital numbers for bands 2 to 8 were noted and input into the MINITAB statistical analysis package. The deep water reflectance values were subtracted from each band and a natural logarithmic transformation was carried out on the data. The resulting values corresponded to x_i which is the variable linearly related to water depth in band i. The measured depths were then correlated with these values.

To examine the relationship between water depths and observed reflectances, the data from the seven bands was then used in a stepwise regression against measured depths so that the best combination of bands could be used for prediction. With these bands identified it was possible to obtain a regression equation which could be applied to the data in order to convert the digital numbers in the bands used, into actual depth values. In addition, an examination of changes in bottom types was carried out by the application of Lyzenga's method of plotting X_i against X_j using bands 5 and 3.

5.4.2. Results

An analysis of the water samples revealed that water turbidity in the study reach is very low (2 to 3 NTU) during the low summer flows and so can effectively be disregarded. However, it was found that the dark colouring of the water in the river at this location, does effect light reflectance. The catchment includes large areas which are covered in peat resulting in high levels of dissolved organic carbon in drainage waters. This gives the river here a dark tint (organic colour) which appears to reduce light reflectance levels and decrease the maximum depth of light penetration.

Table 5.1. shows the correlation of the transformed digital numbers in band 2 to 8 with the measured water depth values. Bands 3 to 6 show good correlations. Table 5.2. shows the results of the stepwise regression.

Table 5.1. Correlation of digital numbers (bands 2 to 8) with water depth.

	x_2	x_3	x_4	x_5	x_6	x_7	x_8
Corr. coeff.	-0.46	-0.71	-0.73	-0.79	-0.76	-0.63	-0.30

Table 5.2. Results of the stepwise regression.

Step	1	2	3	4
Constant	1.2283	1.2547	0.9948	1.0060
x_5	-0.428	-0.278	-0.245	-0.370
T-ratio	-17.02	-5.65	-5.36	-5.38
x_6		-0.198	-0.365	-0.381
T-ratio		-3.50	-6.16	-6.48
x_8			0.309	0.305
T-ratio			5.89	5.89
x_3				0.157
T-ratio				2.41
R^2	61.41	63.85	69.69	70.64

As a result of the stepwise regression, bands 2, 4 and 7 were discarded from the final equation. The regression equation using bands 5, 6, 8 and 3 was calculated as follows;

$$\text{Water Depth} = 1.006 - 0.370\, x_5 - 0.381\, x_6 + 0.305\, x_8 + 0.157\, x_3 \qquad (5.2.)$$

(R^2=71%).

The equation was applied to the logarithmically transformed digital numbers which represent the pixels corresponding to the location of the depth measurements. This allows the predicted depths to be plotted against the actual depths.

Figure 5.3. shows a scatter plot of the measured depths against the depths predicted using the regression equation. The results appear promising between 0 and 60 cm. At depths measured as being greater than 60cm, there appears to be a cut-off which suggests that this is the maximum penetration depth of water for light in these wavelengths. Some values have been classified as minus depth values ie. above the water surface. These are mostly points of very shallow depth anyway and therefore very high reflectance values. In a classification of depths these will be classed as zero values. There are several wildly spurious values.

Using the Idrisi raster based GIS package, the equation was applied to the image area using the four specified bands. The land area was masked off as before. The initial results were 'grainy' so in order to obtain a clearer picture of the results, this image was then filtered with an averaging filter whereby the value of each pixel is taken from the mean of itself and surrounding 8 neighbours. Figure 5.4. shows the resulting image which has been classified into depth classes of 10 cm intervals.

Figure 5.5. is a graph showing the results of Lyzenga's method for examining changes in bottom reflectances. In this case x_i is calculated using band 5, and x_j is calculated using band 3. The results show that in the area of higher natural log values which represent high reflectances and thus shallow water, there is an absence of parallel lines formed by the point

positions which would indicate differing bottom types. In the deeper areas represented by the lower values of x_i and x_j, there is a greater scatter of the data but no distinct parallel lines.

5.4.3. Discussion

The effects of sun-glint were not found to be a problem with the multispectral imagery which scans only the area directly beneath the aircraft. Water surface backscatter in areas of high turbulence however, was more problematic with the values over the riffles, often being given much shallower depth values. Figure 5.3. shows the plot of actual depths against predicted depths. From this it can be seen that some values are even given minus depth values and this may in part, be due to water surface backscatter in these areas. The few spurious points that have much lower predicted depth values than their actual depth are also probably due to light backscatter.

The turbidity of the water measured at the time of the flights was very low and so was not a problem in this study. The dark organic tint of the water however, greatly decreased the depth of light penetration. Figure 5.3. shows a cut-off of the predicted water depth at around 60cm where the data points flatten off. This may be the maximum depth of penetration of light for the study reach although it can be seen in figure 5.4. that some areas have been classified as deeper than this. The cut-off shown in figure 5.3. may therefore be due to a high level of algal covering and thus low bottom reflectance, at the location where some of the cross-sections were taken. The reliability of data classified at 60cm or more, is dubious and must be treated with caution. Experiments with Secchi disks would need to be carried out to determine the extinction coefficient of the water so its effects can be separated from bottom reflectance.

Figure 5.5. shows the plot of x_i verses x_j. The single line of data representing the shallow areas contrasts to the scatter of data representing the deeper areas. This is to some degree the expected result as most of the shallower areas will occur on riffles where the bottom gravels are 'clean' and relatively algal free. In the deeper areas represented by the lower natural log values, there is a much greater scatter of the data points although no distinct parallel lines can be distinguished as described in Lyzenga's paper (1981). This indicates that there are no distinctly different bottom types in the study area but instead, a series of bottom types with progressively darker or lighter reflectance levels. This conforms with evidence in the field which found the bottom type to be relatively uniform but with differing amounts of algal covering depending on the prevalent streamflow conditions in the area. In areas of rapid, shallow flow such as riffles, the gravel has little or no algal cover causing it to have it high reflectance levels. In the deeper areas with a slower water velocity, algal build up on the bottom decreases the reflectance levels substantially. Given the indeterminate nature of bottom reflectance, it is not possible to classify its relative effect in the study area. It does however, serve to over-accentuate the differences between shallow and deep water areas in classifications based on a direct exponential correlation between water depth and reflectance and the method can thus still be used for morphological mapping.

The overall depth classification results are promising and an R^2 of 71% shows that this is a reasonably accurate method for determination of in-channel morphological features for the study area. Due to the cut-off of light penetration and the low bottom reflectance of algal covered sediments, classes deeper than 60cm must be treated with a degree of caution.

5.5. Bathymetric mapping using black and white aerial photography

Multispectral imagery is not often widely available and is usually expensive to obtain. For this reason, the application of image analysis techniques to black and white aerial photography for the purposes of bathymetric mapping, was investigated.

5.5.1. Data acquisition and processing methods

The photographs were acquired from the flights of the 13th of June, 1994. The test site chosen for investigation was Moulinearn which has easy access. The river at this point, exhibits a wide range of water depths and variations in the amount of algal covering on the bottom sediments. Two sets of marker boards were placed on the ground to be used as reference points to locate the positions of the two cross-sections which were surveyed. One cross-section was located so that it crossed an area of deeper but still accessible water. The other cross-section was located across a riffle. The data was used to plot detailed graphs of the water depths for these cross-sections.

The 1994 black and white aerial photographs, provided by NERC, were converted to digital images using a Hammatsu digital camera interfaced with a Hewlett Packard workstation.

Initially, a large magnification was used so that the survey area could be studied in detail. This resulted in an image with a pixel size of approximately 0.7 to 0.8 metres on the ground. The markers on the ground had been placed at fixed distances of 10 metres apart so that the pixel size of captured images could be calculated by using these for reference.

Using the two cross-section graphs, the water depth corresponding to each pixel along the cross-sections was noted giving 206 depth values in all. Two sets of data from the images were noted. Firstly, the pixel reflectance values from the raw images corresponding to the locations of the noted depths were recorded. It was decided, however, that the effects of using image processing techniques on the data be assessed, the end result of which provided the second set of data. The processing consisted of firstly isolating the river by masking the land areas. A linear contrast stretch was then applied which effectively reduced all the lowest values of the image (ie. the deep water reflectance values) to zero, and increased the highest values representing the emergent gravel bars, to 255. All intermediate values were linearly stretched between the two extremes. This image was processed using an averaging (3x3) filter in order to smooth the data.

The two data sets were input into MINITAB along with their corresponding water depth measurements. A natural log transformation was applied to the data sets, so that a linear relationship with water depth was achieved. The resulting values were then correlated with the depth values.

5.5.2. Results

The results of the correlation of data with depth values are shown in table 5.3.

Table 5.3. Correlation coefficients of data sets with measured water depths.

	ln. Raw pixel values.	ln. Processed pixel values.
Correlation coefficient.	-0.743	-0.690

The natural log transformations (ln) of the raw pixel values were regressed against the actual depths and produced a regression equation with a R^2=55.2% which is fairly poor. The data was then split up, so that the individual correlation of the pool and riffle data could be examined. Table 5.4. shows the results.

Table 5.4. Correlation coefficients for pool and riffle cross-sections.

	Pool (raw data)	Pool (processed data)	Riffle (raw data)	Riffle (processed data)
Correlation Coefficient.	-0.806	-0.939	-0.345	-0.310

The problem lies therefore, in the correlation of the riffle data which shows there is a limited relationship between reflectance values and water depth. The main reason for this is likely to be the higher amount of turbulence common over riffles, giving abnormally high reflectance values because of increased water surface backscatter.

The processed data from the pool cross-section was regressed against the corresponding depth values to produce the regression equation:

$$\text{Water depth} = 2.65 - 0.464\, X_i \qquad (5.3.)$$

(R^2=88.1%)

Where X_i is the natural log of processed pool reflectance values.

The scatter plot in figure 5.6. shows the predicted depths obtained by applying this equation to the natural log of the processed reflectance values for the pool cross-section, plotted against the actual depth values. As a better example of the accuracy of this process, figure 5.7. shows the measured cross-sections plotted alongside the cross-section constructed using the depths predicted from the regression equation. The regression equation was applied to the processed image using Idrisi software for a visual analysis of the results which are shown in figure 5.8.

5.5.3. Discussion

The scatter plot of actual versus predicted depths of the pool data (figure 5.6.), shows a high degree of scatter. A visual comparison of the actual and predicted cross-section (figure 5.7.) is much more impressive indicating that there is a great deal of potential in this method. However, the poor results over the riffle area, demonstrate that much more research is needed to resolve the problems that have become evident with the application of this method. It may be the case that the use of colour aerial photography may address some of these problems more successfully.

There are several other difficulties that need to be addressed before this method is utilised successfully. Firstly, the capture of the aerial photographs with digital cameras needs to be investigated. The main problem lies with uneven light source which may illuminate some areas of the photograph more than others. This is very difficult to quantify. Secondly, the problems of uneven contrast within and between the photographs as a result of photographic processing techniques would mean that large amounts of ground-truth data would be needed in any area under investigation. This, in effect, defeats the object of the exercise.

However, despite these difficulties, this method may be used to gain an indication of in-channel morphology without quantification of depths. This may be useful for the examination of channel bedforms and can also be used retrospectively on historical aerial photographs allowing the extension of the temporal scale of a project. The use of the technique would benefit from more research so that the problems can be identified more clearly, and if not resolved, at least defined so that the reliability of data obtained in this way can be established. Due to the problems with the method outlined here, the examination of in-channel morphology for the purposes of this study, were confined to the use of the multispectral imagery.

5.6. In-channel morphology within the study reach

The four study field sites chosen for closer scrutiny in chapter 4 (figure 4.9.) were examined using the 1992 multispectral imagery to determine the nature of their in-channel morphology. A section of imagery was "cut-out" for each site and equation 5.2. was applied using the four specified bands as described in section 5.4. Figure 5.9. to 5.12. show the resulting depth classifications for each of the four sites and figure 5.13. is a depth classification for an additional site which is part of section 4.

The technique was also applied to the 1992 imagery for the whole of sections 1 to 5 and most of section 6. The bottom part of section 6 and sections 7 to 10 were not processed due to the drop-out that was discussed in chapter 3 (section 3.4.). This meant that it was not possible to rectify the images so that quantitative measurements could be carried out. The processed images were rectified (see section 3.4.) and classified into emergent gravel bars and 4 depth classes (1 to 30cm, 31 to 60cm, 61 to 90cm and >90cm.). The resultant maps were simplified by grouping the main areas of each depth class. Figures 5.14. to 5.19. show the simplified in-channel morphology for sections 1 to 6. The total area in each depth class was then calculated for each section and the results are plotted in figure 5.20.

The maps were also used for the examination of pool-riffle spacing. The distances between riffles, were measured and calculated in terms of their relationship to the average channel width of the study reach. Figure 5.21. shows a graph of the riffle to riffle spacing along the length of the study reach.

5.6.1. Discussion

The area of river bank marked on figure 5.9. (field site 1), corresponds to that which has undergone the largest amount of erosion within this study site. The map of water depths shows that the cross-sectional morphology at this particular location is clearly asymmetrical with the deepest part of the channel almost adjacent to the eroding western bank. Similarly, the eroding river bank marked at site 2. and site 4. (figures 5.10. and 5.11.) also have this asymmetric cross-section with the deepest part of the channel directly adjacent to the eroding bank. The shallow, gently sloping inner bank is likely to be prograding and thus providing the driving mechanism for the erosion. In contrast, at site 3. where very little bank erosion was detected between 1971 and 1993, the cross-section is much more symmetrical with a steep sided channel and relatively flat bottom spanning most of the channel width.

These results demonstrate the well known fact, that one of the more important factors in the location of bank erosion is the cross-sectional morphology of the river channel. The nature of asymmetric channel form controlling bank erosion location on concave bank sections also suggests that the river at these locations is tending towards a more meandering planform pattern rather than a braided one. Figure 5.13. shows part of the study reach covered by section 4. This section between 1992 and 1993 (see chapter 4), has been actively eroding on both sides of the channel and the presence of mid-channel gravel bars suggest a more braided planform than those of the other sections. The in-channel morphology shown in figure 5.13. shows this part of the channel to be shallow over most of its width as would be expected with a braided channel. It is clear that due to one or more influencing factors, this section of the study reach has crossed the meandering/braided channel threshold which the other defined sections have not.

The graph in figure 5.20. shows the percentage areas of each depth class that make up the total active gravel area for each section. The percentage areas for sections 2 and 6 are calculated using the total gravel area covered by data rather than for the whole section. It is difficult to draw any significant conclusions from these results but there are a few general remarks that can be made. Sections 3 and 5 which are the two stable sections, have a lower proportions of gravel bar and very shallow (1 to 30cm) water areas than the more unstable areas. Section 1 which was classified as having the highest percentage area of channel change 1971 to 1994 (see table 4.2.), has the highest proportion of gravel bar and very shallow water areas.

The mean riffle to riffle spacing along the study reach was 5.9 channel widths although the individual values varied quite considerably from 2.1 channel widths to 14.9 channel widths. Figure 5.21. examines the riffle to riffle spacing along the length of the study reach and it is interesting to note that the spacing rises sharply at the confluence and returns to more normal levels further downstream. This is due to the existence of a long, deep pool which is consistent with convergent flow conditions caused by the major confluence at this location. Upstream of the confluence however, many of the inter-riffle spacings are less than 5 channel widths.

Leopold et al. (1964) were the first to note that pool-riffle spacing generally was of the order of 5 to 7 channel widths. This figure has been often repeated in the literature as being the accepted value of pool-riffle spacing. Gregory et al. (1994) has tested the validity of these figures. In an analysis of 16 sets of data obtained from the literature, Gregory et al. (1994) found that most of the results lay in the 5 to 7 channel width range despite the fact that the studies had been carried out on rivers varying in width from 4 metres to more than 90 metres. Knighton (1984) suggests that in reality both channel width and pool-riffle spacing are extremely variable even within short reaches. He uses the study by Keller and Melhorn (1973) to illustrate this as they found pool to pool spacing which ranged from 1.5 to 23.3 channel widths with an overall mean of 5.9.

The results of this study agree with Knighton's (1984) proposals and show that although the mean spacing is 5.9 channel widths , the results vary considerably. The generally low figure, especially upstream of the confluence is most likely due to the fact that the measurement of channel width taken as the active gravel area, is higher than the width that would be given by other methods of measurement, such as bankfull discharge.

5.7. Conclusions

1. The use of multispectral imagery with its combination of bands in different wavelengths is a useful and accurate method for the determination of in-channel morphological data for gravel-bed rivers with a high bottom reflectance. With reasonably small amounts of ground truth data available, it is possible for a large area to be mapped for water depth in detail. Problems exist however, with the effects of surface water backscatter, the classification of water depths across riffles, turbid waters and variable bottom reflectance. More research is need to explore these problems and to validate the method.

2. The use of black and white aerial photographs for mapping in-channel morphology is more problematic. The calibration of ground-truth data with reflectance values is not always sufficiently accurate to provide reliable data and the use of colour aerial photographs for this

purpose could be more effective. However, as a method for obtaining relative channel morphology, the technique is promising and is likely to be the only method available which could retrospectively provide data on channel bedform. Further research is needed to address the problems which are the same as those of the method using multispectral imagery with the additional problems relating to those of photographic contrast within and between photographs.

3. The application of the method to the multispectral imagery of the study reach, produced a detailed map of water depths within the channel. They showed the study reach to be mostly of a meandering morphology with the exception of section 4 which, with its wide shallow cross-section and mid-channel bars, was more typical of a braided morphology. Eroding banks were found to be associated with asymmetrical cross-sections with pools directly adjacent to a concave retreating bank opposite a shallow prograding lateral bar. The braided section, however, was retreating on both sides and is associated with the growth of a large mid-channel bar.

4. Inter-riffle distances within the study reach were highly variable. The mean inter-riffle distance of 5.9 channel widths falls within the usual range of 5 to 7 channel widths which is often quoted in the literature.

CHAPTER 6

THE DETERMINATION OF FACTORS AFFECTING CHANNEL STABILITY

6.1. Introduction

The factors which affect the rate and distribution of channel change are discussed in chapter 2 (section 2.6.) and the complex interaction of these variables is summarised in figure 2.3. The three main factors which directly affect channel change can be summarised as sediment dynamics, stream power and bank stability. Sediment dynamics are a complex subject and are not investigated in any detail in this thesis. However, the effects of sediment distribution within the study reach was examined in chapter 5 which detailed the effects of in-channel morphology and river bedform on changes in channel planform.

The second factor is stream power, the magnitude of which is determined by a combination of discharge and channel slope. Therefore, if the value of channel slope is known for a particular reach, the stream power can be calculated for any given discharge. The third main factor of channel change is that of bank stability. This in turn, is a function of bank sediments, bank slope and height, and vegetation, the effects of which are discussed in section 2.6.3. Vegetation also plays an important role in stabilising sediments by recolonisation of areas of aggradation such as gravel bars and abandoned channels. It is the effect of these influences which will be explored in this chapter.

This chapter is divided into two main parts. The first part involves the identification and quantification of channel slope, bank sediments, and bank slope, height and character by means of fieldwork. The affects of these factors on river bank erosion are then analysed using GIS and relational database techniques (section 6.2.). The second part discusses the classification of riparian and floodplain vegetation using remotely sensed ATM data. The relationship between the distribution of vegetation classes and geomorphological surfaces as determined by the positions of old river channels, is explored with a view to analysing their effects on channel instability (section 6.3.). Section 6.4. concludes the chapter.

6.2. Variables identified by fieldwork

The factors which are usually measured in the field that affect river channel changes are as follows:

1. channel widths,
2. channel cross-sections,
3. channel slope,
4. sediment size and movement,
5. bank parameters (height, slope, composition, basal scour and vegetation).

In previous chapters, channel widths and other planform parameters have been discussed and channel cross-sections have been determined by other methods as described in chapter 5. This leaves channel slope, sediment size and movement, and bank parameters which have not been considered.

On a large reach of river such as the one in this study, the amount of information that can realistically be determined from fieldwork is spatially restricted. For example, quantification of bedload yield on a river of such dimensions, would be a problematic and the benefits that could be gained from such a study may well be outweighed by the input of time needed to complete such a job. For the purposes of this thesis, the study of sediment size and movement was thought to be unfeasible. To an extent, the study of channel bedforms in chapter 5, relating the distribution of sedimentation zones to channel planform, addresses the effects of sediment movement on channel change. However, a detailed study on the rates and distribution of sediment movement on the River Tay would be an interesting thesis in itself.

The measurement of channel slope and bank parameters on the other hand, is less problematic and time-consuming. Data relating to these factors were collected for the study reach using traditional methods. However, new methods for the handling and analysis of the data were explored using innovative techniques based on GIS technology.

6.2.1. Measurement of channel slope

Channel slope or gradient is usually obtained from map data by measuring the reach length and the height difference between the upstream and downstream end of the reach. The main problem with this is the lack of height data on maps. The largest scale of map widely available is the 1:10000 OS maps which has contours at 10m intervals. This requires the measurement of long reaches in order to obtain a reasonable estimation of channel slope and so spatial detail is lost. The measurement of channel slope was therefore determined in the field by detailed surveying.

An EDM was used to survey small reaches of the river. It was not feasible to obtain a continuous measurement of channel gradient along the whole study reach as there are some areas where there is no continuous line of sight. However, it was possible to measure the channel gradient in small reaches which exhibited relatively uniform characteristics. Measurements were taken during low flow at the water surface/river bank boundary. The data was downloaded to a PC using LISCAD which made it possible to measure the length of the water surface boundary surveyed and the height difference between the top and bottom of the reach. This method of measuring small height differences on short reaches is greatly facilitated with the use of EDM's which have an extremely high level of accuracy (+/- a few mm). The resulting channel slopes calculated by the survey are shown in figure 6.1.

6.2.2. Determination of bank characteristics

Six main variables were identified relating to river bank characteristics which may have an effect on channel change. These are as follows:

1. Bank height as defined by the height difference between the top of the bank and the water level at low flow,
2. Height of undercutting,
3. Bank slope in degrees from the horizontal,

4. Bank composition,
5. Bank vegetation,
6. Basal Scour.

The first five of these factors were examined and noted in the field but it was felt that basal scour was not easily identifiable by fieldwork. Additionally, it was thought that the study carried out in chapter 5 dealing with channel bathymetry, had already identified areas where basal scour is most important, i.e. where channel cross-section is markedly asymmetrical with the deepest part of the channel directly adjacent to the bank.

In addition to the five factors listed above which were measured in the field, it was noted whether embankments were present, whether or not the bank had a lateral gravel bar, and if the bank was protected from erosion by rip-rap or bedrock.

The fieldwork was carried out in June 1992 around the time of the aerial survey. The river during this time was at a consistently low flow (24 to 26 m^3s^{-1}). Small sections of bank which showed uniform characteristics were identified and the details of these were measured and noted. Bank height and undercut height were recorded to the nearest 25cm and slope was measured and classified into 10^o classes. Three classes of bank composition were identified; those consisting mostly of laminated silts, those consisting mostly of unconsolidated gravels, and those of a composite nature. Ten classes of riparian vegetation were determined and are as follows;

1. grass,
2. scrub (consisting mainly of gorse and/or broom with herbaceous plants and often mixed with young saplings),

3. trees (dominated by Alder, Willow and Birch),
4. dominated by grass with some scrub,
5. dominated by grass with some trees,
6. dominated by scrub with some grass,
7. dominated by scrub with some trees,
8. dominated by trees with some grass,
9. dominated by trees with some scrub,
10. a mixture of grass, trees and scrub.

6.2.3. Data handling methods

One of the most valuable assets of many GIS systems is their ability to be linked with a database. The possibilities created by this were explored for the handling and analysis of the data collected by fieldwork of the bank characteristics. The GIS software used was IDRISI which can be linked with the Dbase III plus database package.

The data for each of the 6 sections surveyed was handled individually and a database file was created for each one. The database was set up with 11 fields (see table 6.1). Each of the small lengths of bank that exhibited uniform characteristics was assigned an identity code which relates to the first field of the database.

Table 6.1. Database fields.

Field name.	Data type.
Identifier code	numeric
Bank height	numeric (cm)
Undercut height	numeric (cm)
slope	numeric (degrees from horizontal)
Embanked?	boolean number
Lateral gravel bar?	boolean number
Rip-rap or bedrock controlled?	boolean number
Bank composition	character (description)
Bank composition code	numeric (composition class)
Bank vegetation	character (description)
Bank vegetation code	numeric (vegetation class)

The data type for the fields relating to the presence or absence of embankments, lateral gravel bars or rip-rap/bedrock is a boolean number. A boolean number is a binary number that indicates the presence of a particular feature by assigning it a value of 1, or the absence of that feature by assigning it a value of 0.

Once the data had been entered into the database, vector maps for each section were constructed to show the positions of each of the bank sub-sections relating to the identifier codes. These maps were to be used to identify the types of bank characteristics which were eroded between 1992 and 1993. In a study of bank erosion using GIS, the spatial errors must be identified and taken into account. In section 4.2.3. the errors in the rectified aerial photograph data are discussed with the conclusion that any change in the bank positions over 5m have a high probability of being due to channel change and not data error. Gurnell et al. (1994) also found the same error margin of 5m in their study of channel change on the River Dee. In order to account for this error the positions the bank identifying vectors, were digitised 5 metres behind the bank lines as depicted on the 1992 maps. This meant that any erosion identified from the overlay of the bank information and the 1993 map would be due to actual erosion and not map error. The amount of erosion would be somewhat underestimated but spurious results regarding the characteristics of eroded bank properties would be avoided.

Using the raster file of the 1992 river channel (5x5 metre pixel size) for each section, a line 5m into the floodplain was constructed using IDRISI's distance program which calculates the distance of each pixel from a given object. This line was then used as a guide for digitising the identified sub-sections which were then given the appropriate identity code. The conversion of this digitised vector file into a raster file resulted in an image showing only the bank line with each pixel coded with an identity number relating to its database record.

Information from the various fields in the database file can be transferred to an IDRISI values file using the DBIDRIS program. The values file will contain each of the identity numbers along with the related numeric value given in the specified field. This file can then be used to substitute the identifier value of each pixel with its actual value for the specified parameter.

The data analysis carried out using the database information is illustrated using the bank height information as an example. Once an image representing bank height had been created by reassigning the bank line identifier image with the actual bank height values, various statistics can be obtained. Firstly, a histogram of the image gives the number of pixels within each height range. Then, in order to determine the number of pixels in each height range that have been eroded between 1992 and 1993, the two images are combined using boolean algebra. A raster image of the 1993 river section is created with the region covered by the active gravel area being given a value of 1. All areas outside this have a value of zero. If this image is multiplied by the raster image that contains the 1992 bank heights, only those lengths of the 1992 bank line that are covered by the 1993 image with a value of 1 will remain in the resulting image. Areas with a value of zero in either the 1992 bank line image or the 1993 gravel area image will have a value of zero in the resulting image. Therefore, pixels containing any value above zero in the resulting image will have been eroded between 1992 and 1993. A histogram of this image will show the number of pixels in each height class that have been eroded.

This method was used to process all the data, resulting in statistics for each section showing the number of pixels in each bank height class, undercut class, bank slope class, bank composition class, bank vegetation class and also the number of pixels representing banks that have a lateral gravel bar, are protected by embankments or by rip-rap/bedrock. The number of pixels in each of those classes that had been eroded between 1992 and 1993 was also calculated. In addition, these statistics were calculated for the whole study reach along with the number of pixels eroded for the different channel gradients measured. The percentage of erosion along the whole study reach was calculated separately for undercut and non-undercut banks.

6.2.4. Results

The percentage of pixels eroded from the total number of pixels was calculated for each parameter and plotted as graphs. Figures 6.2. to 6.6. show these results. In terms of bank height (figure 6.2.) there is nothing conclusive shown by the results. Similarly, in figure 6.3. which shows the range of undercut heights that have been eroded, there is no conclusive trend although it does appear that there is a slight increase in total percentage erosion for increasing undercut height. Figure 6.4. shows the distribution of slope classes for the eroded pixels. Again, no systematic trend is evident although a greatly increased amount of total erosion has occurred in the 81 to 90^0 class compared to that of the lower angle classes. The results for erosion of the different vegetation classes are much more definite. Figure 6.5. shows that areas vegetated by scrub have undergone a much higher percentage of erosion than any other vegetation type. Erosion of the bank composition classes (figure 6.6.) also shows more conclusive results, with composite bank types (composed of interlayered cohesive silts and non-cohesive gravels) having undergone the greatest amount of erosion with those composed of laminated silts having experienced very little erosion.

Of the total length of bank that was protected by embankments within the study reach, only 4% suffered any erosion. The lengths of bank that had a lateral gravel bar underwent 19% of erosion although most of this was due to the extension of the active gravel areas into regions that were previously floodplain and therefore not primary erosion. Of the total length of banks that were protected by rip-rap or were bedrock controlled, only 1% suffered any erosion. With regard to channel gradient, all areas that experienced erosion between

1992 and 1993 had a slope of 0.002 or 0.003 although only two small sub-sections had slopes of lesser values.

For the whole study reach, the number of pixels for undercut and non-undercut banks was calculated. Of the length of banks that were undercut, 22% of it was eroded. Of the banks that were not undercut, 11% of the total was eroded although, a high percentage of this erosion occurred within section 4 which experienced a rapid amount of change during this period.

6.2.5. Discussion

The results indicate that factors such as bank height and slope apparently have little affect on the erosion potential of the river bank within the study reach, or their effects are outweighed by other factors. Undercut height does seem to have a little influence but the results are inconclusive. The evidence shows that undercut banks have undergone twice as much erosion as non-undercut banks. The undercut banks however, are already being eroded and so are most likely to continue being eroded. The erosion of the non-undercut banks during the 1992 to 1993 period is most likely due to rapid expansion of the channel's active gravel area caused mainly by the January 1993 flood. It is probable that during a more usual flow regime, without extreme flood events, the percentage of erosion of non-undercut banks is much lower than that of the undercut banks. Extreme flows will cause bank stability thresholds to be exceeded for the non-undercut banks causing initial undercutting and leaving the bank exposed and much more vulnerable to erosion during less extreme conditions.

The most important factor relating to bank erosion probability, appears to be bank composition. Banks with inter-layered cohesive and non-cohesive sediments have undergone the most erosion with those consisting of non-cohesive gravels also having quite high amounts. The erosion of banks consisting of cohesive, laminated silts was very low. The river banks composed of composite and gravel sediments indicate that they are located in areas of former channel activity whereas banks consisting of laminated silts, suggest that the area has remained a stable part of the floodplain for a considerable time. There are far fewer undercut banks consisting of laminated silts than those of gravels and those of a composite nature indicating that the channel is preferentially reworking formerly active areas. The higher bank resistance of the cohesive silts is an example of positive feedback whereby previously stable zones of the floodplain maintain their stability through bank resistance. The unstable areas with their non-cohesive sediments, remain unstable due to the low resistance of the typical sediments formed in these environments.

The analysis of bank vegetation shows that areas dominated by scrub have undergone by far the greatest amount of erosion in comparison to the other vegetation classes. However, this does not mean that the plant species comprising this group provide less cohesion for the bank sediments compared to other classes. Indeed, Broom and Gorse which make up a large proportion of this group, have very deep, strong fibrous roots which would be expected to aid erosion resistance. A more likely explanation for these statistics, is that this particular plant group is the most suitable for growing on the loose, unconsolidated sediments typical of formerly active channel areas which have been shown to be the most likely to be eroded.

6.3. The use of remotely sensed data to examine the composition and distribution of vegetation

Hooper (1992) carried out a detailed study of the relationship between vegetation communities and hydrogeomorphic characteristics of riverine systems. The basis of the study is that the distribution and composition of riparian and floodplain vegetation communities are related to inundation characteristics (flood frequency, intensity and duration). The study identified an inundation gradient with respect to vegetation communities but Hooper noted that the relationship may have been an indirect one and that other factors such as substrate and soil moisture will also affect the vegetation distributions. Furthermore, Hooper notes that vegetative evidence may be used as an indicator of fluvial landforms and that it may be possible to look for vegetation contrasts at a largely unknown site and use them to evaluate geomorphic surfaces present.

Channel movement in gravel-bed rivers often occurs as a result of the formation of gravel bars, both lateral and medial. Progressive aggradation of these bars, forces erosion on opposing banks and the bars are subsequently stabilised by a sequence of vegetation colonies. The process of colonisation results in positive feedback, as was noted by Leopold and Wolman (1957), whereby initially small hardy plants will be established which encourages further deposition and stabilisation of sediment during overbank flow. This in turn provides a good growing surface for successively larger plant species. An account of the growth of a shingle island by Coates (1906) on the River Tummel at Ballinluig beautifully illustrates this process:

> *"The pebble beds in the shallow parts of the stream are constantly growing by the addition of pebbles which the stream with diminishing velocity, is no longer able to transport, until at length they become "stanners" or islands of shingle in the middle of the stream. Next, pods of broom floating down the river get stranded among the pebbles, and the hardy seeds take root in the spring. This forms a foothold for other seeds, as well as for sand and gravels, until in course of time, the surface of the stanner gets bound by a covering of herbaceous vegetation. Next the cones of the Scots fir from the upper reaches of the valley get washed up on the shore, until at length a woody island is formed, such as we see at so many points in the Tay and its tributaries." (page cxvi to cxvii)*

Cecil (1990) describes in more detail the vegetation successions found in the colonisation of shingle islands on the River Feshie. Three different stages in the colonising sequence were found:

1) The early colonising vegetation which forms patches on the bare gravel. This is typified by species such as wild thyme (Thymus drucei), horseshoe vetch (Hippocrepis comosa), sheeps sorrel (Rumex acetosella) and mosses as well as shingle species like sea campion (Silene maratima).

2) The next succession is formed by established grassy heath type vegetation which has a higher species diversity and includes many of the early colonising species as

well as species such as mouse-ear hawkweed (Pilosella offcinarum), heather (Calluna vulgaris), fairy flax (Linum catharticum), common milkwort (Polygala vulgaris) and autumn gentian (Gentianella amarella).

3) The third succession shows the beginnings of woodland vegetation where the trees are starting to shade out many of the early and heathy grassland species.

In consequence of these factors, it may be possible to use information on the various riparian vegetation communities to gain an indication of underlying substrate and to assess qualitatively, the relative ages of the active regions of the floodplain. On the assumption that the younger areas of the floodplain and those with a loose unconsolidated substrate, would have a lower inherent stability than the older regions or those with more stable sediments, it is possible that an index of stability could be determined based on these vegetation communities. This section of the chapter explores the possibility and usefulness of using airborne ATM data to carry out a broad scale classification of the floodplain vegetation. The results are related to former channel positions that are documented on maps in order to examine the relationships and possibly determine the relative ages of formerly active channels by vegetation type distribution.

6.3.1. Classification of Vegetation

Firstly, methods of classification of the remotely sensed data must be examined and their accuracy assessed. In this section, various methods are discussed and an accuracy comparison of two methods is carried out.

6.3.1.1. Theoretical background

Two types of classification procedure are available; unsupervised and supervised. In unsupervised classification a number of bands (usually three) are used and the distribution of reflectance values are examined. Classification is based on the various clusters formed by this data. Unsupervised classification is mostly used for data exploration purposes in order to investigate whether ground classes can be discriminated and whether classes are pure or mixed (Mather, 1987). The disadvantage of this method however is that the clusters formed by the data do not necessarily correspond to the classes of interest to the user.

Supervised classification of data relies on more user interaction. It is a two stage process;

1. Identification of classes of interest and the characterisation of these classes through statistics.
2. Pixel by pixel classification of images using a numerical rule which uses these statistics (Swain, 1978).

In order to identify the classes and produce statistics, training areas on the image must be established. These are identified by the user by various means and digitised as vector files onto the image. Software routines are then employed to extract the statistical data. There is some debate as to the ideal number of pixels that are optimum for the definition of a training area. Lillesand and Keifer (1979) suggested that the minimum number of pixels used should be n+1 (n=number of bands) but in practice 10n to 100n is ideal. Mather (1987) suggested 30n as the optimum value although Hooper (1992) noted that in riparian areas it may only be possible to collect smaller training sets. As far as possible, training sets need to be obtained in areas of uniform characteristics for the class of interest with no mixed pixels included.

In using ATM data to classify vegetation, Hooper (1992) commented that it was not possible to identify individual species from ATM imagery unless it formed mono-specific stands. Also the nature of species mixture in riparian areas means many different types of species in small areas. The benefits of a very detailed classification in the context of this study would not provide increased benefits sufficient to outweigh the greatly increased effort needed to achieve it. As a consequence of this, a very broad classification system was used within this area.

6.3.1.2. Classification method

The area of Tomdachoille Island was selected to examine the accuracy and usefulness of using supervised classification of vegetation using ATM imagery. The area is part of the

SNH designated Shingle Islands SSSI composed of five areas which were first notified in 1955. The shingle islands are described in the 1985 notification as:

> *"A series of extensive riverine shingle islands in various stages of colonisation from bare shingle to mixed woodland, and including old abandoned river channels. These areas are particularly notable for the large number of plant species present, including plants characteristic of woodland, open shingle habitats, mire, montane cliffs and unimproved grassland, with a number of uncommon species represented."*
>
> (NCC 1985, page 1)

In 1987 the area was surveyed and classified according to the NVC habitat classes as can be seen in figure 6.7. This map was used as a basis for identifying classes and training areas of the vegetation from the 1992 infra-red photographs. Nine major classes could be visually identified from the photographs. These classes are:

1. water,
2. bare shingle,
3. short vegetated shingle,
4. light scrub, dominated by broom (Cytisus scoparius),
5. dark scrub, dominated by gorse (Ulex europaeus),
6. bare soil,
7. unimproved grassland,
8. improved or rich grassland,
9. woodland.

Training areas were then identified (figure 6.8) and a field survey was carried out for verification.

The software used for the image classification was IDRISI. The training areas were digitised and used to create raster polygons. IDRISI's MAKESIG software was used to create signature files which recorded the means, minimums, maximums and standard deviations of digital numbers found in each identified training area. Figure 6.9. shows a graph of the class means extracted.

The ATM imagery consists of 12 bands whereas the maximum number that can be used for classification in IDRISI is 7. Bands 2,4,6,7,8,10 and 11 were chosen to give a wide range of light wavelengths, with more bands in the infra-red part of the spectrum where vegetation reflects more light. Two types of supervised per-pixel classification routines were used on this area in order to compare the accuracy of each. The first was a minimum distance classification; a procedure which classifies each pixel according to the signature file with the nearest mean. The second program used was a maximum likelihood classification which assigns each pixel to a class based on a comparison of probability for each class. The probability is calculated according to the mean, maximum, minimum and standard deviation of the signature file. The maximum likelihood classification works very well when training areas are well defined but often performs badly when broad classes are used (IDRISI technical reference manual). The minimum distance classifier often performs better in areas with broad classification classes.

6.3.1.3. Classification results

The resulting two classifications can be seen in figures 6.10. which is the minimum distance classification, and 6.11. which is the maximum likelihood classification. In order to establish the accuracy of these images, ground truth areas for each class that were independent of the training areas, were interpreted from the aerial photographs. These were digitised as polygons and the resulting areas were cross-tabulated with both the classified images. The results are shown in tables 6.2. and 6.3.

Table 6.2. Cross-tabulation results for the minimum distance classification.

class no.	1	2	3	4	5	6	7	8	9
1	1344	0	0	0	0	0	0	0	54
2	0	747	5	0	0	0	0	0	0
3	0	31	131	0	0	0	1	0	0
4	0	0	0	61	3	0	0	1	1
5	0	0	0	0	129	0	1	0	0
6	0	0	6	0	0	413	2	0	0
7	0	0	0	1	12	0	362	3	0
8	0	0	0	0	0	0	0	309	62
9	0	0	0	1	0	0	0	0	494
Chi-Square=29344.88 df=64 Cramer's V.=0.94 Overall Kappa=0.95									

Table 6.3. Cross-tabulation results for maximum likelihood classification.

cat no.	1	2	3	4	5	6	7	8	9
1	1314	0	0	0	0	0	0	0	0
2	0	588	4	0	0	0	0	0	0
3	0	190	138	0	0	2	22	0	0
4	4	0	0	63	5	0	160	0	0
5	0	0	0	0	135	0	58	0	0
6	0	0	0	0	0	411	0	0	0
7	0	0	0	0	0	0	126	1	0
8	0	0	0	0	0	0	0	244	7
9	26	0	0	0	4	0	0	68	604
Chi-Square=22914.04 df=64 Cramer's V.=0.83 Overall Kappa=0.84									

The results of the cross-tabulation of the ground truth image with the two classifications show that the minimum distance classification routine achieved a high level of agreement with the ground-truth data compared with the maximum likelihood routine. This is due to the fact that broad classification classes are being used which do not suit the maximum likelihood method. In the minimum distance classification the main source of confusion occurred in the areas of woodland. This is a result of the high resolution of the imagery which means that light variations across the tree canopy caused by the texture of the wooded stand, are picked up in great detail. This results in tree shadow being confused with water and the most brightly lit parts of the canopy being confused with improved grassland. However, on the whole the accuracy of the classification is high and therefore the results are valuable for the purposes of habitat mapping.

6.3.2. Data analysis

The other images for the study reach were classified using the minimum distance method. The images were then converted to Laser-Scan's DTI format where they were then converted to vector files for geometric rectification as described in section 3.2.. The images comprising each of the unstable sections (1, 2, 4,and 6) were pasted together and converted back to raster files and then imported back into IDRISI. The active areas of the floodplain (ie. those shown as occupied in the 1863, 1899, 1975 and interpreted as occupied from Roy's 1755 map) were isolated and the areas outside this were masked off. Figures 6.12., 6.13., 6.14. and 6.15. show the resulting images for the four unstable sections.

For the purposes of data analysis the two scrub classes were joined together to form one single class. The total number of pixels in each classification class for the active floodplain area, were noted using IDRISI's histogram package. Images for the channel positions in 1863, 1899 and 1975 were constructed for each section. The area of channel in each of these was given a value of 1. When these were multiplied with the classified images of vegetation, the resulting image shows the vegetation classes only for the areas occupied by the channel for the particular date used. The rest of the image is reclassified as zero. A histogram of this resultant image gives the number of pixels for each vegetation class in the area occupied by a channel for the chosen map date. The number of pixels in each class for the area of formerly occupied channel, was calculated as a percentage of the total number of pixels in that class for the whole of the active floodplain area. This had the effect of creating a comparable measure for each of the vegetation classes on the areas occupied by channels for the three map dates used.

6.3.2.1. Data analysis results

Figures 6.16. to 6.19. show the results of the analysis for sections 1, 2, 4 and 6. For all the sections, there is a high proportion of water and bare shingle in the areas formerly occupied by the channels at all three dates, indicating a high degree of re-working. The results for the areas covered with vegetated shingle are variable but are generally much lower for the 1975 channel area than for the 1863 or 1899 occupation area. This demonstrates that areas undergoing stabilisation by vegetation in 1975 have mostly remained stable. The results for the other vegetation classes vary between sections. In section 1, the vegetation type most common in the areas occupied by channels in 1863 and 1899 is scrub closely followed by bare soil and sand which is also the most common type for the 1975 channel areas. The least common vegetation type on the former channels is woodland. Alternatively, for section 2, the most common type of vegetation is woodland apart from the 1863 area much of which has been used for agricultural purposes and is improved grassland. In section 4 it is scrub that is the most common vegetation on occupied area but the figure for woodland is also high. For section 6 however, it is bare soil and sand that is the most common followed by scrub and woodland. Figure 6.20. shows the overall means of vegetation types on former channels for all the sections. This shows that scrub is the most likely vegetation type growing on former channels followed by woodland, then bare soil/sand areas, unimproved grassland with improved grassland being the least common.

6.3.3. Discussion

The results of the vegetation classification are good for the minimum distance method. A 94% agreement was achieved with the resulting classification and air-photo' interpretation data; the main source of confusion was in woodland areas. The results of the data analysis showing distribution of vegetation types on former channels was less promising. No one vegetation type was dominant on former channels for all the sections and much variation seemed to exist between sections. Scrub was fairly common to most of the former channels however, and overall was the most common is these areas. Woodland was common on former channels only in some sections. In the areas formerly occupied by the 1975 channel, the most common surface type is vegetated shingle followed by scrub and then woodland. This would appear to be the broad successional sequence for vegetation recolonisation of the study reach although the actual sequence for each unit area will vary around this depending on other factors such as inundation and seed dispersal.

There are several reasons why the results of this analysis were disappointing. Firstly, the position of former channels does not necessarily relate to surface type as a former channel may have been abandoned as a result of gravel deposition or gradually infilled with a mixture of silts and layers of gravel deposited during flood flows. The other factor is that the positions of former channels obtained from the 1863, 1899 and 1975 maps are only 'snap-shots' and do not take into account the fact the channel may have migrated across other areas between map dates. A much more detailed investigation is needed where a field examination of surface types can be related to vegetation composition and distribution.

The high level of accuracy achieved by using ATM data for broad scale vegetation classification of riparian areas, provides a high potential for other uses of the data. Habitat classifications for example would be of great use in management of riparian areas. The combination of the use of classified remotely sensed data and GIS techniques also provides wide ranging possibilities for data analysis.

6.4. Conclusions

1. The influence of bank height and slope either appear to have little effect on erosion rates or their effects are outweighed by other factors.

2. The high percentage (11%) of erosion of non-undercut river banks between 1992 and 1993, is most likely due to the rapid expansion of the channel during the 1993 flood event. The river banks that were already undercut before this period underwent twice as much erosion between 1992 and 1993, as the non-undercut banks. It would seem that these extreme floods cause the river bank stability thresholds to be exceeded in the non-undercut banks which then greatly facilitates further erosion.

3. The most important factor in the study reach which affected the rate and distribution of river bank erosion between 1992 and 1993, was bank sediment composition. The composite river banks and those consisting of non-cohesive sediments underwent far greater amounts of erosion than those of laminated silts. Section 4.3.4. identified most of this erosion as occurring during the 1993 flood event and so it appears these bank compositions are the

most susceptible to erosion during high magnitude events. The large proportion of erosion in areas of composite and gravel banks indicate a high degree of reworking of old sediments within the active area of the floodplain.

4. Scrub was the most commonly eroded bank vegetation type. An analysis of vegetation distribution on former channels indicates this to be common on formerly active areas of the floodplain. Its high erosion probability is therefore, more likely due to the fact that these species colonise the more unstable areas of the floodplain, rather than a poor ability to provide cohesion for sediments. This factor must be one borne in mind for studies of the effects of vegetation on rates and distribution of bank erosion.

5. A possible broad successional sequence of vegetation on the 1975 channel area was highlighted. The youngest areas consist of vegetated shingle followed by scrub and then woodland. This however, varied from section to section and other factors must be influential.

6. The minimum distance classification of the ATM data provided a high accuracy of results for broad vegetation classes. However, the data analysis of vegetation distribution relating to geomorphic surfaces, provided inconclusive results. The method could be improved by further investigation into the relationships of surface type, surface age and vegetation based on a more field orientated study as opposed to one based on map information. The potential uses of the classified habitat data and the combination of this and GIS methods, are wide ranging and would benefit from additional study.

CHAPTER 7

SPATIAL MAPPING OF BANK EROSION PROBABILITIES

7.1. Introduction

In this chapter the potential of modelling the spatial distribution of erosion probabilities is explored. The complex nature of fluvial processes makes precise predictions virtually impossible, however a probabilistic approach may provide enhanced predictive capabilities (Graf, 1984). Section 7.2. outlines the theory of a method of spatial probability assessment developed by Graf (1984) and section 7.3. explores the development of GIS capabilities which allow the utilisation of this method. The use of GIS techniques allows this method to be extended by the incorporation of other influential variables (section 7.4.). Section 7.5. examines possible refinements to the model and includes the resultant maps of predicted erosional probabilities for three given flood events. Section 7.6. concludes the chapter.

7.2. Spatial method of probability zoning

In 1984, Graf produced a paper entitled "A probabilistic approach to the spatial assessment of river channel instability" which details a method for assessing erosion risk based on the spatial location of areas of the floodplain relative to the position of the river channel and incorporating values for flood return periods. The areas of floodplain surrounding the river channel are divided up into cells and the location of each cell is classified according to its distance upstream and laterally from the active river channel. In the example given by Graf, the location of each cell was determined and classified by hand. However, the use of cells and spatial analysis lends itself extremely well to the use of raster based GIS techniques which allow the method to be utilised with ease on long reaches of river channels. This section describes in detail the theory behind the method.

7.2.1. Theoretical background

The theory behind Graf's method is based on the concept of spatial autocorrelation. The fundamental principle of spatial autocorrelation is that there is a systematic (usually exponential) decline in neighbouring influence as distance increases. This concept is coupled with the fact that there is a view in fluvial geomorphological literature (eg. Gregory, 1977), that suggests the probability that any region of a near channel surface (such as a cell) will be eroded during a particular time period. is dependent on its location with respect to the active channel and the magnitudes and frequencies of the floods during the intervening period. Location of each cell relative to the active channel is most important in the upstream and lateral direction (Graf, 1984). Graf (1984) accounted for flood magnitude and frequency by calculating the sum of the recurrence intervals of the peak annual floods during the period in question. Therefore the probability that a given cell will be eroded by a channel in a specified time period is given by the equation:

$$P_{i,j}=f\left(d_l, d_u, \sum_{t=1}^{n} r\right) \tag{7.1}$$

where $P_{i,j}$ is the probability of erosion ($0<p_{i,j}<1$) for a cell at co-ordinates i,j; f is a function; d_l is the distance laterally across the floodplain from a cell to the nearest active channel; d_u is the distance upstream along the floodplain to the nearest active channel; r is the return interval of a peak annual flood; t is a year; and n is the number of years in the period of interest.

In fluvial research, distance terms have been shown to be related to magnitudes by power functions (Leopold et al., 1964) therefore, the form of function f is likely to be a power function. Fluvial processes and discharge measures are also commonly related by power functions so that equation 7.1. can be redefined as:

$$P_{i,j}=a_0\,(d_l)^{b1}\,(d_u)^{b2}\left(\sum_{t=1}^{n} r\right)^{b3} \qquad (7.2)$$

where a_0 and $b_{1,2,3}$ are empirically derived constants based on the historical record. Given empirical observation for $P_{i,j}$, d_l, d_u, and r, equation 7.2. can be converted to its linear form:

$$\log_{10}P_{i,j}=\log_{10}a_o+b_1\,(\log_{10}d_l)+b_2\,(\log_{10}d_u)+b_3\left(\log_{10}\sum_{t=1}^{n} r\right) \qquad (7.3.)$$

The constants can then be determined using a standard least squares solution. Empirical values for ordered sets ($P_{i,j}$, d_l, d_u, and the sum of the return intervals) can be obtained from transition matrices such as the one shown in table 7.1. which is the example given by Graf (1984).

Table 7.1. Transition matrix for the Lower Rillito Creek, 1918-1937 (after Graf, 1984). Sum of the return intervals is 132; c is the total number of cells with indicated distances; c_e is the total number of cells eroded during the period, and $p_{i,j}$, is the observed probability of erosion (c_e/c).

Lateral distance (m)	statistic	Upstream distance (m)			
		100	200	300	400+
100	c	59	20	23	78
	c_e	30	3	13	9
	$p_{i,j}$	0.51	0.15	0.57	0.12
200	c	0	6	15	89
	c_e	0	2	2	2
	$p_{i,j}$	-	0.33	0.13	0.02
300	c	0	0	7	29
	c_e	0	0	1	0
	$p_{i,j}$	-	-	0.14	-
400	c	0	0	0	11
	c_e	0	0	0	0
	$p_{i,j}$	-	-	-	-

So, for example, by taking the data from table 7.1., the ordered set for cells located 100m laterally from the channel and 200m downstream from the channel for this period is (0.15, 100, 200, 132). Each period of analysis produces a transition matrix containing several ordered sets. Several periods of analyses provides sufficient data to solve equation 7.3. by the least squares solution and so obtain the empirical values for a_0, and $b_{1,2,3}$. Using the defined coefficients, calculations of probability of erosion can then be made for various time periods and flood return intervals. The input of hypothetical floods by means of their return periods allows erosion probabilities to be determined for a variety of scenarios. The probabilities for the erosion of cells can also be mapped to represent the spatial variability of erosion.

Graf applied his model to the Rillito Creek situated on the northern edge of Tuscon, Arizona. Twenty-five maps for various dates were available for the study area spanning 108 years in addition to which, a lengthy hydrologic record was available. This provided an unusually extensive data set on which the model was tested. Correlation coefficients of 0.728 and 0.785 were obtained for two separate periods with corresponding R^2 coefficients of determination of 0.530 and 0.617. In a discussion of his results Graf (1984) noted that the probability of erosion for a given cell is reasonably accounted for by the two location variables and the data from the annual flood series. However, he also notes that the functions are not perfect predictors because of the complex variables that are not accounted for and that predictability may be enhanced by the inclusion of factors such as bank materials, soils, vegetation, sediment discharge and water discharge.

The method outlined above was applied to the study reach on the Rivers Tummel and Tay, using the data supplied by the processed aerial photographs (see chapter 4). This represents a very short time-scale of analysis (5 years) compared with that used by Graf (1984) so the relevance of the method is tested with regard to a different temporal scale. The intervals between the photo' dates include two extreme discharge events and so the method's relevance to flood damage prediction is also tested. The data from the 1971 photographs were not used due to the long time gap between this and the 1988 photographs. The time intervals between the other photo' dates are all much shorter and it was thought that the inclusion of the 1971 data would unduly influence the results. Evidence of channel changes on the study reach indicate that they are mostly a result of large events and recovery is fairly rapid. Therefore, using a long time interval between mapped channel dates may not allow the influence of individual events to be determined.

The spatial scale used in this study is also markedly different to that used by Graf whose cell sizes were 100m by 100m. The amount of erosion which occurs in the study area over the short time-scale used, is such that maximum amounts of erosion between map dates rarely exceeds 15m. Therefore a different spatial scale of analysis is required. This again tests the validity of the method's application to different fluvial environments.

A refinement of the method is explored with regard to the use of flood return intervals which are substituted in favour of empirical values derived from discharge measurements of the largest annual flood occurring during the period in question, and channel slope.

7.3. Application of model

In this section, the method of automated spatial classification using GIS techniques, is described. This is followed by the determination of the flood return periods and discharge statistics. Using the information derived, the method is tested and the results discussed.

7.3.1. Automated spatial classification

The maps produced for the active channel areas derived from the 1988, 1992, 1993 and 1994 aerial photographs were divided up into the previously delimited sections and converted to raster files with pixels of 5x5m. The images consisted of boolean numbers where the pixels representing active channels were assigned a value of 1 and those representing no-channel were given a value of 0. The directional classification of floodplain cells was achieved by using a series of specially constructed image filters and a combination of Laser-Scan's software routines. Table 7.2. shows the distance definitions of the eighty different classes that were defined in the directional classification of floodplain cells.

Table 7.2. Definition of classes used in floodplain directional classification routine. (Numbers corresponding to a pair of upstream and lateral distances are the defined classes.)

Lateral Distance.	Upstream distance.								
	5m	10m	15m	20m	25m	30m	35m	40m	>40m
5m	80	71	62	53	44	35	26	17	8
10m	79	70	61	52	43	34	25	16	7
15m	78	69	60	51	42	33	24	15	6
20m	77	68	59	50	41	32	23	14	5
25m	76	67	58	49	40	31	22	13	4
30m	75	66	57	48	39	30	21	12	3
35m	74	65	56	47	38	29	20	11	2
40m	73	64	55	46	37	28	19	10	1
>40m	72	63	54	45	36	27	18	9	0

So for example, to classify all the cells in class 80 (within 5m upstream to the active channel and within 5m laterally to the active channel) a 3x3 filter was constructed with the following values:

$$\begin{matrix} 0 & 1 & 0 \\ 5 & 0 & 5 \\ 0 & 0 & 0 \end{matrix}$$

This was passed over the image so that the resulting value of the centre pixel is the sum of the product of the corresponding kernel and matrix values as demonstrated in the example below.

Matrix	**Kernel**	**Output**
0 0 1 1 1		
0 **0 1 1** 1	**0 1 0**	**5 6 11**
0 **0 0 1** 1	**5 0 5**	**0 6 6**
0 **0 0 1** 1	**0 0 0**	**0 5 6**
0 0 0 0 1		

In the output image, all cells with a value of 6 or 11 satisfy the requirements for that current class. Values of 0, 1, 5 or 10 do not. The resulting image is then edited so that values of 6 and 11 are given a value of 80 and all others are reclassed as zero. The area representing the river channel is then reassigned an arbitrary value (eg. 100) that does not represent any class so that only floodplain cells are classified. In the example shown therefore, the resulting central values in the original matrix would be:

$$\begin{matrix} 0 & 100 & 100 \\ 0 & 80 & 100 \\ 0 & 0 & 100 \end{matrix}$$

In order to classify cells further than 5m away from the active channel, minus values and thresholds needed to be introduced into the filtering process. The determination of class 69

(10 metres upstream and 15 metres laterally to the active channel) is used as an example. For this a filter kernel 7 x 5 was defined with the following values:

$$\begin{matrix} 0 & 0 & 0 & 1 & 0 & 0 & 0 \\ 0 & 0 & 0 & -15 & 0 & 0 & 0 \\ 5 & -15 & -15 & 0 & -15 & -15 & 5 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 \end{matrix}$$

If the central pixel in the matrix is within less than 10 metres upstream or 15 metres laterally of the active channel the product of filtering using this kernel will be a minus figure. A threshold value was set at zero so that all minus values would automatically be reset to zero. As in the example for class 80, values of 6 and 11 would satisfy the class requirements and values of 0, 1, 5 or 10 would not.

In this manner, a separate filter kernel was produced for each class and the use of each of these on the boolean image representing the channel at a particular date, produced a new image. The whole process was written into a command file whereby as each new image was created, it was added together with the previous one and the channel areas reset to a value of 100. The final image resulting after all 80 filters had been used, was the completed classified image. Figure 7.1. shows an example of a classified image (the 80 classes are grouped together into 10 larger classes due to the restricted number of colours available for image reproduction).

Classified images for 1988, 1992 and 1993 were constructed for each section and a histogram of each one gave the statistics of the number of cells in each class. By using boolean multiplication, the next image year was overlaid onto this. A histogram of the resulting image provided the statistics of the number of cells in each class which were eroded in the intervening period. This resulted in statistics for 3 periods (1988 to 1992; 1992 to 1993; and 1993 to 1994) which could be used in the statistical analysis.

7.3.2. Incorporation of discharge statistics

The method of spatial probability assessment developed by Graf (1984) uses the sum of the annual flood return intervals as a measure of the effect of river discharges. These will also be used in this study, but an additional method of assessing the effect of discharges will be tested to see if results can be improved. The use of flood return periods does not take into account the effect of local conditions such as channel slope which may increase or lessen the erosional powers of a flood discharge. The use of stream power is explored here as an alternative measure. Stream power can be defined by the equation:

$$\Omega=\rho g Q s_e \tag{7.4}$$

where Ω is stream power in watts per metre; ρ is the density of water (1000 $\mathrm{kgm^{-3}}$); g is gravitational acceleration (9.8 $\mathrm{ms^{-2}}$); Q is discharge and s_e is the channel slope. Specific stream power is calculated by dividing the stream power by channel width and is usually a more accurate indication of the energy expended by a given discharge. However, in this case it was thought that specific stream power was an inappropriate measure as the large flood events were overbank flows and so not confined within the channel width. Seven subsections were determined from the slope survey (section 6.2.1.). Sections 2 and 4 were divided into 3 and 2 sub-sections respectively. Sections 1 and 6 remained the same as they exhibit a fairly uniform slope throughout their lengths. The specific stream power for the largest flood occurring during the three periods, was calculated.

Figure 7.2. shows the graph of the flood return intervals for Port-na-Craig gauging station as calculated by the Tay River Purification Board. Table 7.3. shows the discharges of the annual floods and their return intervals, for the three time periods used in this study.

Table 7.3. Discharges and sum of return intervals for annual floods in the three time periods used for probability analysis.

Time period	Annual flood discharge.	Sum of return intervals.
1988 to 1992	676	29
	970	
	416	
	406	
1992 to 1993	1048	40
1993 to 1994	516	2

The stream power for the largest floods that occurred in each period are given in table 7.4.

7.3.3. Initial results

The flood return and stream power information along with that derived from the classified images completes the data requirements for the ordered sets. The sets were input into MINITAB giving a total of 1681 sets. However, only 595 sets could be used to solve the equation as some of the sets had missing values which were due to either an observed probability of zero of which there is no log value, or where the upstream or lateral distance is greater than 40m and has no observed value.

The equation was solved using the least squares method, firstly, using the sum of the flood return period as the third variable and, secondly, using the calculated stream power as the third variable. Table 7.5. shows the results.

The results of the regression were poor as shown by the low R^2 given in table 7.5. and a further analysis was carried out on each sub-section (as defined by channel slope) in order to determine if the poor results are due to the different sections responding in different ways. As the results were better for the analysis which included the sum of the flood return periods, this will be the third variable used in the solution. Table 7.6. shows the results.

Table 7.4. Stream powers for largest flood occurring in each of the three periods used in the probability analysis.

Section number	Time period	Discharge of largest flood	Channel slope	Stream power. (watts m^{-3})
1	1988-1992	970	0.002	19012
	1992-1993	1078		21129
	1993-1994	516		10114
2a	1988-1992	970	0.003	28518
	1992-1993	1078		31693
	1993-1994	516		15170
2b	1988-1992	970	0.0002	1901
	1992-1993	1078		2113
	1993-1994	516		1011
2c	1988-1992	970	0.003	28518
	1992-1993	1078		31693
	1993-1994	516		15170
4a	1988-1992	970	0.0002	1901
	1992-1993	1078		2113
	1993-1994	516		1011
4b	1988-1992	970	0.003	28518
	1992-1993	1078		31693
	1993-1994	516		15170
6	1988-1992	970	0.002	19012
	1992-1993	1078		21129
	1993-1994	516		10114

Table 7.5. Solution of equation 7.3. for the study reach.

Statistic	Solution using the sum of flood return periods.	Solution using stream power.
R^2, coefficient of determination.	14.4%	9.9%
S, standard error	0.354	0.363
F, regression F ratio	33.12	21.66
p, confidence interval	0.000	0.000
n, number of cases	595	595
a_0, coefficient (log value)	-0.0797	-0.4802
b_1, exponent	-0.284	-0.258
b_2, exponent	-0.369	-0.357
b_3, exponent	0.191	0.148

Table 7.6. Solution of equation 7.3. for each sub-section.

Stat	sect. 1	sect. 2a	sect. 2b	sect. 2c.	sect. 4a	sect. 4b	sect. 6
r^2	49.2%	11.7%	47.3%	59.1%	50.0%	20.4%	37.0%
S	0.2508	0.2865	0.2929	0.2206	0.2885	0.4128	0.2816
F	46.84	4.29	3.29	32.27	9.99	10.00	19.55
p	0.000	0.007	0.062	0.000	0.000	0.000	0.000
n	149	101	15	71	34	121	104
loga_0	-0.270	-0.507	-0.475	0.545	-6.275	0.143	0.859
b_1	-0.479	0.170	-1.47	-1.12	0.690	-0.680	-0.622
b_2	-0.351	-0.198	0.752	-0.044	-0.351	-0.268	-0.712
b_3	0.526	0.110	0.070	-0.026	3.78	0.259	0.0659

7.3.4. Discussion

The results shown in table 7.6. show that the results between sub-sections are highly variable with some showing a good correlation of the variables with probability of erosion and other giving a very poor correlation indeed.

Clearly, erosion risk should decline with increasing distance of a floodplain cell from the active river channel and therefore, exponents b_1 and b_2 should have a negative value. In addition, erosion risk should increase with floods of a greater return period (or during a period with a higher sum of return periods), and so exponent b_3 would be expected to be positive.

Section 1 shows the best results overall with 49% of erosion probability explained by the three variables. Both the exponents relating to the lateral and upstream distances have the expected negative values and the exponent relating to the flood return period has the expected positive value. The lateral distance is shown to be more important than the upstream distance by the higher value of b_1 than b_2. The effect of flood return periods also has a high significance shown by the value of exponent b_3 being greater than for nearly all the other sections. Section 1 also has the highest number of ordered sets (n) for the solution of equation 7.3..

The results for section 2a. are poor with very little of the erosion probability explained by the variables. Section 2b. has a high R^2 value but with only 15 ordered sets to solve the equation, the results are not reliable. Section 2c. also has a high R^2 value. The extremely low values of exponents b_2 and b_3 however, indicate that lateral distance to the active channel is the only significant variable of the three used to determine erosion probability (this is supported by the high p-values for upstream distance and sum of flood return period variables which are 0.664 and 0.577 respectively; p-value for lateral distance is 0.000).

Section 4a. shows a good correlation, but the positive value of b_1 and the low number of ordered sets (34) used for the solution, indicates that the results are probably not reliable. Section 4b has a lower R^2 value, but the exponents show the expected negative and positive values. A high number of ordered sets (121) were used to solve the equation and the poor results are most likely due to the greater importance of other variables not included in this analysis. Section 6 has similar results to those of section 4b, although the low value of exponent b_3 suggests that flood return periods do not have a high significance in this area.

Overall, the results show that in some of the sections, the effects of lateral and upstream distance to the active channel along with flood return periods, have a greater importance than in others. The variability of success of the method's application to the different sections, indicates that these may respond in different ways to the effects of influencing factors.

The poor results also indicate that other factors not taken into account in this analysis, have a high significance in the determination of erosion probability. Graf (1984) came to the same conclusions in his study on the application of this method, to the Lower Rillito Creek. Graf's study had the benefit of a long hydrological record and many different maps from which to obtain planform information. The R^2 coefficients for determination in Graf's study were 53.0% and 61.7% for two time periods. In this study the most reliable results (for section 1) gave an R^2 of 47.3% which is only slightly lower. This indicates that with the benefit of more data, the results may be improved. This similarity in results for the two studies is supporting evidence for the hypothesis that this method is applicable to different rivers, as well as different spatial and temporal scales.

7.4. Incorporation of other influential variables

In order to improve the results obtainable by this model, the incorporation of other variables will be examined. Chapter 5 highlighted the importance of cross-sectional shape and form of a channel on the distribution of bank erosion. Retreating banks were almost always associated with an asymmetric channel cross-section where the deepest part of the channel was directly adjacent to the retreating bank. An improvement to the model would undoubtedly result from incorporation of an asymmetry index (eg. Knighton, 1881; Milne, 1983) into the model. The channel bathymetry maps produced in chapter 5 could be used for the automated production of an asymmetry index for floodplain pixels adjacent to the channel. However, such an automated classification would be a complex procedure requiring specialised programming skills and such a task, was thought to be unfeasible within the confines of this project.

Chapter 6. examined the effects of other influential variables which included bank height, bank undercut height, bank slope, bank vegetation and bank composition. The chapter concluded that bank composition was by far the most important factor in determining bank erosion. Banks vegetated by scrub had a high probability of erosion but these results were thought to be more likely due to the fact that scrub was common on the highly erodable bank composition types. Undercutting of banks also appeared to be of high significance, with those already undercut twice as likely to be eroded than non-undercut banks. Banks that were protected by rip-rap or embankments had a very low probability of being eroded.

7.4.1. Production of erosion risk map

The effects of bank composition, presence or absence of undercutting, rip-rap/bedrock and embankments, were incorporated into the model in an attempt to improve prediction of erosion probability.. The individual effects of these variables is difficult to quantify. However, their relative effects can be assessed. It has been shown that banks protected by rip-rap or bedrock, have a very low probability of being eroded. Banks protected by embankments have a slightly higher chance of erosion but it is still relatively low. Banks with neither rip-rap/bedrock or embankments but are not undercut have a higher likelihood of erosion. Undercut banks are the most likely to be eroded but of these, those composed of silts are less likely to be eroded than those composed of gravels or of a composite nature. Using this information, a scale of erosion risk can be constructed using these five criteria outlined. Banks with the lowest erosion risk, ie. those protected by rip-rap or bedrock, are given a value of 1, and those in the highest risk class, ie. undercut banks composed of gravels or interlayered gravels and silts, are given a value of 5. The information obtained in chapter 6. is used to construct this risk map. Figure 7.3. shows an example of a risk map constructed for section 1.

In order to test the validity of this classification, the probabilities of river bank erosion were calculated by determining the number of cells in each erosion risk class within 40 metres (any direction) of the active channel, and the number of cells eroded during the three time periods (1988-1992, 1992-1993, 1993-1994). The erosion probability for each erosion risk class, in each period was calculated by dividing the number of eroded cells by the total number of cells. Table 7.7. shows the erosion probability for each erosion risk class during the three time intervals.

Table 7.7. Erosion probability for each erosion risk class.

Risk class	Erosion probability 1988 to 1992	Erosion probability 1992 to 1993	Erosion probability 1993 to 1994
1	0.08	0.05	0.04
2	0.12	0.10	0.05
3	0.13	0.15	0.04
4	0.10	0.06	0.15
5	0.24	0.18	0.06

The results shown in table 7.7. show that the erosion risk classification works well with erosion probability increasing with each risk class. The only class that does not conform to the expected results is class 4 which represents undercut banks composed of cohesive laminated silts. For the first two time periods, the probability is very low which might indicate that banks of these type should be in a lower risk class. However, in the period 1993 to 1994, the probability of erosion is much higher than for all the other values whose low values for this period are due to the lack of a large flood event. These differences indicate that the cause of erosion of these banks is different than for the other classes. The apparent lack of relationship between amount of erosion and flood return intervals suggests that erosion of this class is not related to fluvial activity.

Thorne (1982) noted that undisturbed cohesive banks are much less susceptible to fluvial erosion than non-cohesive banks. Much erosion of non-cohesive banks occur by means of mass failure of blocks. The motivating force behind this is the weight of the potential failure block (Thorne, 1982) which would be expected to increase when it is saturated, either from heavy rainfall or subsequent to high river flows. Therefore, in highly cohesive sediments such as found in the study reach, erosion would not be expected to be related directly to river channel flows and flood events, but more probably to wetting and drying cycles. As a result of the unpredictability of erosion of this class, all erosion probabilities calculated for this class must be treated with caution.

7.4.2. Inclusion of erosion risk into model

Data on the number of cells in each classified distance category, were determined for each of the five erosion risk classes and the number of these cells eroded in each category and class allowed the erosion probabilities for each to be determined. This resulted in ordered sets for the solution of equation 7.3. but with an extra variable representing risk class.

7.4.3. Results

Table 7.8. shows the results for the solution of equation 7.3. using data from the whole study reach.

Table 7.8. Results of solution of equation 7.3. using the additional variable of erosion risk class (exponent b_4) for the whole study reach.

Statistic	Solution results.
r^2	29.0%
S	0.3075
F	36.29
p	0.000
n	360
$\log a^0$	-0.076
b_1	-0.453
b_2	-0.455
b_3	0.256
b_4	0.490

7.4.4. Discussion

The results are greatly improved with the inclusion of the erosion risk data but the R^2 value of 0.29 still indicates that erosion probability is still not fully explained by the variables included in the equation. The main cause of the poor results could be due to the calculation of the probability itself. In order to explain the source of the problem, an example of one of the transition matrices used for the probability calculation is given in table 7.9.

Table 7.9. Transition matrix for section 2a.

Lat dist (m)	stat	Upstream distance (m)								
		5	10	15	20	25	30	35	40	>40
5	c	53	40	23	13	9	8	5	6	243
	c_e	26	17	12	10	7	8	4	4	84
	$p_{i,j}$	0.49	0.43	0.52	0.77	0.78	1.00	0.80	0.67	0.35
10	c	6	8	18	24	17	13	10	6	296
	c_e	3	3	5	6	6	5	6	5	53
	$p_{i,j}$	0.50	0.38	0.28	0.25	0.35	0.38	0.60	0.83	0.18
15	c	4	4	4	5	14	18	11	10	328
	c_e	1	2	2	3	3	2	2	3	45
	$p_{i,j}$	0.25	0.50	0.50	0.60	0.21	0.11	0.18	0.30	0.14
20	c	3	4	3	3	3	3	12	16	351
	c_e	1	2	2	2	2	2	2	2	34
	$p_{i,j}$	0.33	0.502	0.67	0.67	0.67	0.67	0.17	0.13	0.10
25	c	3	5	2	3	2	3	3	2	375
	c_e	2	2	2	2	2	2	2	2	19
	$p_{i,j}$	0.67	0.40	1.00	0.67	1.00	0.67	0.67	1.00	0.05
30	c	3	5	2	2	3	2	1	2	378
	c_e	2	2	2	2	2	2	1	1	19
	$p_{i,j}$	0.67	0.40	1.00	1.00	0.67	1.00	1.00	0.50	0.05
35	c	2	3	2	0	0	0	1	0	390
	c_e	1	1	1	0	0	0	0	0	19
	$p_{i,j}$	0.50	0.33	0.50	0	0	0	0	0	0.05
40	c	1	1	1	1	0	0	0	0	394
	c_e	0	0	0	0	0	0	0	0	21
	$p_{i,j}$	0	0	0	0	0	0	0	0	0.05
>40	c	3	7	8	7	5	4	3	3	n/a
	c_e	0	0	0	0	0	0	0	0	n/a
	$p_{i,j}$	0	0	0	0	0	0	0	0	n/a

Table 7.9. shows the disparity in the number of cells (c) in each class. For example, the line of the matrix representing cells 25m laterally to the channel shows very few cells in each class with a given upstream distance but a large number of cells where the upstream distance is greater than 40m. The resulting probabilities for this lateral distance are all very variable and show no pattern whatsoever relating to the upstream distance. This is mainly due to the lack of cells in the classes from which probability can be calculated. The matrix tends to show that the more cells in each class, then the lower the erosion probability. A tendency of more cells within 5m laterally and upstream to the channel, results in a low probability when a high one would be expected. Therefore, the lack of data for probability calculation seems to cause spurious results. This would also explain the high variability in results between sections whereby some sections will have far fewer cells in each class than others which will influence the probability calculation.

7.5. Model refinement

A possible solution to the problem of inaccurate probability calculation, is to discard the variable of upstream distance and recalculate values of c, c_e and $p_{i,j}$ for each lateral distance class. By doing this, the number of cells in each lateral distance class become approximately the same or, are at least of a comparable order and with a sufficient number of cells in each class to allow a much more representative calculation of probability. These were calculated for each lateral distance class within each erosion risk class producing the ordered sets:

$$(P_{i,j},\ d_l,\ er_c,\ \sum_{n}^{t=1} r)$$

where er$_c$ is the erosion risk class. The ordered sets were then used to solve the newly defined equation 7.5.:

$$\log_{10}=\log_{10}a^0+b_1(\log_{10}d_l)+b_2(\log_{10}er_c)+b_3(\log_{10}\sum_{n}^{t=1} r) \qquad (7.5)$$

7.5.1. Results

Table 7.10. shows the resulting statistics from the solution of equation 7.5.

Table 7.10. Statistics determined by solution of equation 7.5.

Statistic	Solution results.
r^2	72.9%
S	0.2573
F	71.82
p	0.000
n	84
$\log a^0$	0.7252
b_1	-1.94
b_2	0.737
b_3	0.195

Thus the equation:

$$\log_{10}P_{i,j}=0.725-1.94\log_{10}d_{l}+0.737er_{c}+0.195\left(\sum_{n}^{t=1}r\right) \tag{7.6.}$$

can be used to predict erosion probability for the study reach which can be spatially mapped using GIS. The use of lateral distance only, simplifies the process hugely and renders the use of complex spatial classification procedures unnecessary. Most GIS software packages include distance calculation routines. Therefore the distance classification only needs an outline image of the river channel which can then be run through one such simple program. IDRISI's routine DISTANCE produces a image in which each pixel is classified by distance to a given object. This program was used on the 1994 image of the study reach. The resulting image was used along with the erosion risk image, to calculate the spatial distribution of erosion probability for three given flood events (5, 10 and 25 years), using equation 7.6. The resulting maps (figures 7.4., 7.5. and 7.6.) are classified into 10 categories representing class intervals of 10% probability.

7.5.2. Discussion

The high R^2 value of 72.9% shows the huge improvement in accuracy that the redefined model provides compared to the previous one which incorporated the upstream distance. The method could be improved further by a closer examination of erosion risk categories especially in areas of cohesive bank materials. The effects of floods of various return periods could also be improved with the inclusion of data from more time periods. A consequence of the use of only three time periods in this study, may be that the effects of various flood return periods might not have been accurately calculated and more data would be desirable. The effects of flood duration are also not accounted for. In the period of study, the 1990 flood, although of a lesser magnitude than that of 1993, caused a greater amount of damage in the study area due to its longer duration (section 4.5.). As mentioned in section 7.4., inclusion of a channel asymmetry index should improve the results even more as this was found to be a highly significant factor and has not been accounted for in the model.

However, despite some minor problems, the method is shown to be highly promising. The simplification of the technique with the use of lateral distance only, means that this method can be widely utilised with the availability of basic GIS software. The spatial mapping of predicted erosion probability could be extremely valuable for river management, floodplain hazard zoning and also predicting the effects of hypothetical flood events.

The data set derived from aerial photographs of the study reach is an exceptional one with small time gaps between each photo'-date. This wealth of data was only possible through the NERC airborne remote sensing campaign who carried out several surveys of the study reach within a few years. In normal circumstances, aerial surveys would be carried out at approximately 10 year intervals. In the study reach, where channel change and recovery is rapid, the effects of individual events would be masked with the use of longer time intervals however, in areas of slower and more gradual change such as meandering rivers, the longer time intervals may be more suitable.

The use of remotely sensed satellite images of large, rapidly changing rivers may be an ideal form of data for use with this method. Satellite data is usually regularly obtained with fairly short time intervals between coverage of an area. The co-registering of images of different dates is relatively simple and the data is already in raster format which is suited spatial analysis. If a good hydrologic record accompanies regular satellite data, this method could be used to determine highly accurate erosion probability predictions for large active river systems.

7.6. Conclusions

1. The results of the application of Graf's method (1984) are poor.

2. The inclusion of erosion risk data based on field observations of bank characteristics, improves results.

3. The inclusion of upstream distance in the method, causes an uneven spread of data within the various defined classes which has a detrimental effect on the calculations of erosion probability. The method proposed which uses only lateral distance, provides greatly improved results.

4. The resulting simplification of the technique means that it could be a widely utilised method for erosion probability prediction as it requires only basic GIS software.

5. A good accompanying hydrologic record is necessary for the use of this method.

6. In rivers of rapid channel change and recovery, small time periods are required for the analysis. Larger time intervals may be used however, for slower changing rivers.

7. Satellite data would be ideally suited for use in the application of this method to large, rapidly changing rivers.

8. The refined technique proposed, could provide accurate erosion probability mapping which may be utilised for effective river management, floodplain hazard zoning and predicting the effects of hypothetical flood events.

CHAPTER 8

CONCLUSIONS

8.1. Introduction

In the first chapter of this thesis (section 1.5.), the aims and objectives of the study were detailed. The overall aim of the project was to determine the nature and causes of channel change within the Tay river system. The information derived was to be used in the production of a predictive model for the spatial mapping of erosion hazard probabilities.

Firstly however, appropriate techniques for assessing channel change on the River Tay and for examining the causes of channel change, were to be developed. These techniques were to be based on the new technological developments in GIS and remote sensing methods.

The five specific objectives of the project are given below.

1. To develop the use of GIS techniques for the study of channel change on relatively sizeable rivers and to assess the usefulness of the methods used.
2. To examine the use of remotely sensed data (both aerial photography and ATM data) for identifying 2 and 3-dimensional channel change.
3. To quantify rates and types of channel change that have occurred within the study reach on both a short and long term basis.
4. To determine the principal controls on channel instability within the study reach.

5. To produce a predictive model of channel change for the study reach.

In this chapter a review of the success in achieving each of the five specific objectives is presented (sections 8.2. to 8.6.). Section 8.7. discusses the wider applicability of the techniques developed in this study, for the examination of river channel changes and section 8.8. examines the geomorphological implications of the River Tay study for other Scottish rivers. Section 8.9. proposes further related research.

8.2. The development of GIS techniques for the study of channel change along the study reach

The advantages of using GIS for the study of river channel change are that it allows the direct overlay of map data and remotely sensed data, even when the original scales differ. This can be achieved by simple rectification processes as long as good quality ground control points are available. The map features can be stored in different layers and be given different codes allowing the selection of any combination of stored data for visual or quantitative analysis and map output.

Another advantage of GIS, is that errors can easily be quantified. This is achieved by the ability of GIS systems to measure X Y positions of reference points on different maps which can be used to calculate the root mean square error of the data. It is vitally important that all errors are quantified so that they can be taken into account in the analysis of data.

The input of aerial photograph data and its subsequent scale and distortion correction by data transformation, is also a fairly straight forward procedure using GIS. The accuracy is slightly less than for map data but it allows the direct comparison of data from aerial photographs which would be extremely difficult without GIS.

Once the map data has been input into a GIS, not only is direct qualitative comparison of maps and aerial photographs made possible, it also allows the quantitative analysis of the data which is extremely accurate and simple. Measurements of active gravel areas, channel widths, sinuosity, and braiding index were easily achieved for each of the different maps that were input. In addition, the conversion of the vector data into raster format allowed much more complex analyses to be carried out. The simple and multiple polygon overlay techniques as described in section 4.2.4., are very useful for the examination of environmental change. The use of boolean algebra on multiple images also allows a detailed spatial analysis of areas of change between map and/or photograph dates.

The combination of GIS and database software adds another dimension to the possibilities offered by GIS. Information from classified or field data can be stored in the database and related to an image by identifier codes. The identifier code can then be substituted for the actual value of any specified parameter in the database so that these values can be mapped for visualisation or analysis of their spatial distribution. This facility of GIS was used for the detailed examination of river bank parameters as determined in the field. Histograms of images constructed for each parameter from database substitution, allowed a detailed breakdown of their distributions. Overlaying of images constructed from subsequent photographs allowed the analysis of bank parameters that underwent erosion. This is a very useful facility of GIS and the level of information that can be obtained from this method would be very difficult to achieve by conventional means.

Finally, the ability of GIS software to map spatial distances from features proved valuable in this study, for the production of a predictive model. This was combined with images constructed using data derived from other sources (erosion risk and flood return periods) by means of a mathematical formula to produce an erosion probability map. Image combination by user specified formulae, was also made use of to map water depth for the study section. This feature of GIS makes an ideal tool for spatial modelling of any sort and was found to be particularly useful in this study.

In terms of the specific software used in this study, it was found that the Laser-Scan software was excellent for digitising of maps and aerial photographs, image correction, overlaying of vector data and map production. The IDRISI software however, was better for the analysis of raster data and spatial modelling.

8.3. The use of remotely sensed data for identifying 2 and 3-dimensional channel change

Section 3.4. examines the use of remotely sensed data for the examination of floodplain sedimentary features with a view to extending the temporal record of channel change. Figure 3.6. shows the detail of floodplain features that can be observed using the thermal infra-red band (band 11) of ATM data. With GIS rectification techniques, these features can be overlaid onto a base map. However, the wealth of detail can be somewhat confusing as illustrated in figure 3.7b. and it proved difficult to reconstruct fluvial activity using this information. It does though, give an indication of areas of instability previous to the earliest map date.

The use of aerial photographs in chapter 4. for mapping of recent channel change proved useful. The rectification accuracy was reasonable (<6.1 metres). Problems resulted from availability of good quality data previous to 1971 and the availability would have been more problematic with respect to recent data had it not been for the NERC remote sensing campaign. Other problems arose in the delineation of bank lines where trees lined the river's edge. Active gravel area was used to define the boundary of active river channel in order to overcome the problems of varying water levels between photo' dates although this caused some inaccuracy with regard to freshly deposited gravels subsequent to flood flows.

The use of ATM data for the purposes of bathymetric mapping proved highly successful. Detailed morphological maps were produced of the study area which would have proved difficult to achieve by conventional means. However, these were of limited use in this study due to the lack of later data from a different date with which to compare it.

The use of black and white aerial photography for this purpose proved problematic although preliminary results showed some potential. It is likely that this method cannot be used for quantitative mapping of river bathymetry, but it could be useful for qualitative mapping of in-channel features. Aerial photo's are much more readily available than multispectral data and they could also provide retrospective information on in-channel morphology.

The classification of ATM data for the production of riparian habitat maps was accurate and successful. The class detail of the classification was low which was a result of the fine resolution of the data and the mixed nature of riparian habitats. For the purpose of this study, which was to use vegetation information to map geomorphic surfaces, the use of habitat maps was limited. However, if subsequent ATM data had been acquired, the classified maps would have been useful for documenting habitat change.

8.4. Channel change within the study reach

This section will be divided into three parts; the first describes changes that have occurred in the study reach over geomorphic time and the second describes changes that have occurred over engineering time. The third part, attempts to piece together the temporal and spatial linkages of channel change within the study reach. This will highlight common themes of channel change which are evident along the whole study reach and throughout the timescale used in this study.

8.4.1. Geomorphic time

Chapter 3. via the use of historical map data, documents the planform changes that have occurred within the study reach over the last few hundred years. This allowed the delineation of sections which had been historically unstable braided sections or stable, single- thread channels.

Roy's map, although of dubious accuracy, shows the study reach to have a highly braided planform with multiple mid-channel islands. The 1863 OS map shows a similar picture although the channel appears to be less braided than that depicted on Roy's map. By 1899, many of the mid-channel islands had joined together and some of the channels in the multi-threaded reaches were reduced in size. By 1975, the channel had become mainly single thread with few mid-channel islands. The remote sensing study of floodplain features shows the other channels in the multi-thread section as having been abandoned and gradually infilled as the main channel had become more dominant.

The huge decrease in channel planform dimensions within the study reach which was slight between 1863 and 1899, and dramatic between 1899 and 1975, could be due to several factors. These are outlined below.

1. The lack of severe floods between the 1950s and pre-1990s may have caused channel shrinkage. Although this may have been a contributory factor which accelerated the change during this period it is unlikely to be the main cause. Results from chapter four show that recovery of channel dimensions subsequent to large flood events, is rapid due to vegetation recolonisation.
2. The decrease in channel planform dimensions may be a results of upstream impoundment as a result of the construction of the Pitlochry dam (in 1950). This phenomenon has been observed several times in studies of other rivers. Richards (1982) notes that reservoirs are important in terms of changes in discharge as it dampens flood peaks and in upland gravel-bed rivers, this causes a reduction in channel capacity (Petts, 1979). In a study of 13 reservoirs in Britain, Petts (1979) found an average reduction in channel capacity of 52% whilst Gregory and Park

(1976) working on the rivers Nidd and Bush found reductions of 60% and 34%, respectively. This reason does not explain however, the reduction in channel planform dimensions that started to occur between 1863 and 1899 and the apparent reduction in channel size between 1755 (Roy's map) and 1863. In addition, the study of floodplain sediment features shows much wider channel occupation previous to 1863.

3. An increase in channel capacity, which has occurred as a result of channel incision, has led to a reduction in channel planform dimensions. This may have occurred as a lag effect from the building of channel embankments along the study reach in the early to mid 19th century. Embankments will cause accelerated flow during high magnitude events that are confined within them. This leads to an increase in bedload transport causing scouring and incision resulting in an increase in channel capacity and a subsequent decrease in channel width (Richards, 1982).

In reality, it would be extremely difficult to disentangle the causes of such a major change in channel dimensions and it is likely that all three factors outlined above will have had some effect. It is probable however, that the construction of embankments may have had more of a controlling influence than the other two factors.

8.4.2. Engineering time

The use of aerial photographs and GIS methods allowed a detailed analysis of channel change along the study reach that occurred between 1971 and 1994. Between 1971 and 1988 there was an average decrease of 7.1% in the active gravel area along the study reach. This occurred mainly by means of vegetation recolonisation. The period 1971 to 1988 coincided with in increase in mean annual discharge and the amount of small magnitude events (less than 1000 m^3s^{-1} at Caputh) but there was also a lack of high magnitude events.

The effects of the two major flood events in February 1990 and January 1993 were considerable. Average increases in active gravel area of 6.8% between 1988 and 1992 and of 5.2% between 1992 and 1993 occurred along the study reach. Field investigation of the effects of the 1993 flood showed that a large amount, if not all, of this change occurred during the flood event. The subsequent average decrease in active gravel area (5.2%) that occurred between 1993 and 1994 by vegetation recolonisation, demonstrates the rapid recovery of the study reach subsequent to flood flows. It follows then that channel change in the study reach can be interpreted as being mainly in response to flood events. Lewin's (1989) catastrophe related floodplain seems to be an appropriate definition for the study reach whereby the morphology can be interpreted as a response to, or recovery from rare events. Lewin et al. (1988) noted similar findings on the River Tywi which is described as having a transitional pattern similar to the study reach. In their study, floods were found to generate major lobate, gravel-bed forms with avalanche faces and a multichannel system. Between floods a reversion to a meandering channel with bars, occurred.

It is difficult to deduce long term river trends from a short term study, but it would appear that the study reach is in a form of dynamic equilibrium with fluctuations in that equilibrium caused by change and recovery related to large flood events.

Figure 2.2a. is a diagram of the cusp catastrophe surface as defined by Thom (1975). In Graf's example (1979, 1988) which relates this surface to river channel change, the independent threshold is sinuosity/braiding (whereby the cusp represents the meandering/braided threshold), and the dependent variables are bank resistance and stream power. Figure 2.2c. probably best represents the situation in the historically unstable sections of the study reach. Previous to a major flood, the river banks are vegetated and not undercut but are composed of non-cohesive of composite sediments. A major flood will cause the bank stability threshold to be surpassed abruptly (represented by crossing the steep part of the cusp) by undercutting the banks and exposing the vulnerable sediments which are then easily eroded. A braided planform develops with multiple gravel bars within the channel. Subsequent, lower flows rework the sediments; the gravel bars become attached to the floodplain and are gradually recolonised by vegetation. This causes an eventual return to a single-thread meandering channel.

The data analysis on the individual sections demonstrated that the greatest amount of change occurred within those defined as historically unstable in chapter 3. This confirms that these sections tend to remain unstable which is most likely due to lower inherent thresholds within them compared to the stable sections as a result of less cohesive bank sediments.

8.4.3. Linkages

The dissection of spatial and temporal scales in this study served to identify in detail, changes that have occurred in the study reach. However, there is great benefit in re-constructing the spatial and temporal dimensions in order to determine common linkages in the underlying forms and processes relevant to the study reach. Thorne et al. (1993) studying the River Brahmaputra in Bangladesh for example, determined that channel forms and processes on several levels of scale (both spatial and temporal), were inextricably linked. A brief outline of their findings is presented here to demonstrate these linkages.

Thorne et al. (1993), describe features of the braided River Brahmaputra, on three distinct, hierarchical spatial scales. The 1st order spatial scale relates to that of a series of alternating island and nodal reaches that were identified by Coleman (1969). The islands measure in tens of kilometres relating to the width of the primary channel, and evolve over decades or centuries. They are formed by clusters of braid bars that combine and stabilise. Erosion of islands occurs by embayment in the sides of islands resulting from adjacent bar growth, or by dissection by sub-channels formed along topographic lows in the island which are exploited by high flood flows. However, historic maps show that although erosion and accretion of islands is a continuous process, and altered the shape of islands considerably, a semi-permanent, central core always remained in the same geographical location preserving the position of the island for decades or longer. The upper elevation of island tops corresponds to the height of the surrounding floodplain and are only inundated during high flood flows. The island reaches are separated by relatively stable and narrower, nodes.

On the 2nd order hierarchical scale are braid bars. These are smaller in length and relate to the width of the major channel anabranches. The bars change annually although are rarely totally destroyed and tend to persist in a given location for a number of years. Bar growth is by lateral accretion and bars tend to migrate downstream. As they grow, they tend to deflect flow causing local bank erosion of the adjacent floodplain or island. The upper elevation of bar tops corresponds to just below the height of the dominant discharge. The height of dominant discharge on the Brahmaputra, is lower than the height of bankful discharge. The 3rd order scale identified by Thorne et al. (1993) was that of bedforms which they have not discussed in detail.

There are several factors which are common to the present study, and that of Thorne et al. (1993). The study reach used for this thesis, also exhibits well defined island and nodal reaches (termed unstable and stable sections respectively in this study). Although many of the unstable, multithreaded sections have now become single thread, the historical maps show them to consist of larger, often well vegetated islands with an associated series of smaller bar forms. The larger islands relate to the 1st order hierarchical scale in that they are the largest and most persistent of the features found in the river, while the bars, relate to the 2nd order scale in that they are smaller and have shorter lifespans. Most of the unstable reaches no longer consist of islands and multi-threaded reaches due to the long-term channel shrinkage resulting from anthropogenic activity, and so they are not so easily recognisable as such. This study has shown however, that these unstable zones are still persistent features, in that the greatest amount of channel change occurs in these sections due to an inherent instability resulting from their sediment composition. However, the 1st hierarchical scale, has essentially been masked and channel changes now manifest themselves in these sections, primarily, on the 2nd order hierarchical scale by the formation of small bar forms which deflect flow and cause localised bank erosion. These bar forms are often short-lived and a lack of large flood events will cause them to be incorporated back into the floodplain.

The “nodal reaches”, or those termed stable sections in this study, have also been found to be persistent features in the study reach both on the long and short time-scales. These sections have been shown to experience the least amount of change during flood events. It is unclear why these “nodal reaches” have remained so persistently stable over time, and further research is needed into this phenomenon of alternating stable and unstable reaches, to decipher why such patterns emerge in rivers of this type.

8.5. The principal controls on rates and distribution of channel changes within the study reach

Within the study area, channel changes occur mainly in response to flood events which have been shown to cause rapid amounts of erosion and gravel deposition within short time periods. Recovery by vegetation recolonisation is also relatively rapid with freshly deposited flood gravels being covered by vegetation within one to two years of a flood event.

Channel avulsion episodes are relatively rare within the study reach at present but occurred several times in the past as a result of flood events. Embanking and possibly associated incision has prevented such episodes more recently. However, it is likely that if embankments are not maintained, then breaches occurring in zones of instability may give rise to avulsion episodes.

The "driving mechanism" for bank erosion appears to be sediment deposition in the form of gravel bar development. Accretion and extension of lateral gravel bars, restricts channel capacity and redirects the channel thalweg onto the opposing river bank causing localised bank erosion and thus increasing channel sinuosity. The in-channel morphology in these reaches showed the channel cross-sectional form to be highly asymmetric with the deep part of the channel adjacent to the eroding bank.

It is likely that channel avulsion episodes that occurred in the past were also a result of in-channel deposition. A channel bed locally elevated above the surrounding floodplain by in-channel deposition during flood events, could lead to reoccupation of former channels or floodplain lows scoured out by flood flows.

The field study showed that the most vulnerable areas to erosion during flood events were those that consisted of non-cohesive sediments. This was confirmed by the study in chapter 6 where banks of non-cohesive sediments and those composed of interlayered cohesive and non-cohesive sediments, underwent by far the greatest amount of erosion. The sections of the river defined as historically unstable in chapter 3., would be mostly composed of these sediments as they were formally braided channels with multiple gravel-bars. Thus, it is probable that it is the sediments that cause perpetuation of instability in these historically mobile reaches.

8.6. An appraisal of the predictive model of channel change created for the study reach

The spatial probability method of erosion mapping proposed by Graf (1984) produced poor results in this study. The reason for this is thought to be due to the inclusion of upstream distance which detrimentally effects the calculations of erosion probabilities. However, with the exclusion of upstream distance and the inclusion of an index of erosion risk, the results derived are vastly improved.

The model produced still has some flaws however. The small number of periods used in the study may mean that the effect of flood return periods may not be sufficiently accounted for. The model also does not take into account thresholds which have been shown to be important within the study reach. Lower magnitude floods have very little impact in comparison to high magnitude floods and this is the most likely consequence of the presence of thresholds. In the model produced, the effects of flood magnitudes are calculated as exponential but no threshold value is included. The method is promising though, and at least provides some indication of the spatial distribution of erosion hazards that could prove invaluable to floodplain management decisions by determining the most vulnerable areas of the floodplain.

8.7. Wider applicability of the techniques developed in this study

The use of GIS within the confines of this study proved highly successful. However, the techniques used are widely exportable to other projects provided some considerations are borne in mind. The quality of data analysis that can be achieved is directly reliant on the scale and accuracy of the input data (either maps or aerial photographs). Errors in OS 1:10000 map data have been given as +/- 3.5 metres and errors in these maps which have been scale corrected and overlain using GIS methods, are in the region of +/- 5 metres. A similar figure was determined for the accuracy of the aerial photograph data. Therefore, the spatial and/or temporal scale of a feature under investigation must be of an order whereby 5 metres is relatively small compared with the amount of change that is expected to occur. Large rivers with highly active channels, may benefit hugely from the use of satellite data with GIS spatial data comparison techniques for channel change studies. Satellite data has extremely frequent coverage (LANDSAT, up to every 16 days; SPOT up to every 26 days) with a reasonable resolution (LANDSAT MSS 80x80 metre pixels; LANDSAT TM 30x30m pixels; SPOT 20x20 metre pixels) although it is somewhat expensive to obtain.

The use of GIS in combination with a database package is an excellent method for analysing spatial data and would be appropriate to any size or scale of study provided that the initial planform data is suitable. The method of spatial probability modelling of river bank erosion proposed in this study, has been shown to be transferable to different spatial and temporal scales provided that appropriate data (both map and hydrologic) is available. Again, large highly active rivers would be ideal for analyses of this type in conjunction with satellite data.

The classification of ATM data for mapping in-channel morphology had limited application in this study except for use in assessing the effects of bedforms on river planform change. Rivers with greater problems associated with in-channel deposition may benefit from studies of this type. ATM data however, is expensive, difficult to obtain and, sometimes, turbulence affecting the aircraft during data acquisition creates problems in geometric rectification resulting in high spatial errors. In much larger rivers of a scale which allows study by satellite data, the method may provide a valuable means for mapping in-channel morphology. However, this technique is reliant on a fairly high level of water clarity and so would not be appropriate for turbid rivers. In addition, excessively deep rivers would also be difficult to map due to a limited depth of light penetration which will vary between rivers. A general guide however, is that if in-channel features can be determined visually in the appropriate wavebands of the remotely sensed data, then it is likely that they can be accurately mapped using remotely sensed techniques. Ground truthing must be carried out and located with reference to fixed control points that are identifiable on the imagery.

The use of image analysis techniques on black and white aerial photography for determining in-channel features appears to be promising for use on gravel-bed rivers. Qualitative changes may be determined on small reaches over 30 to 40 year timescales depending on the availability of aerial photographs. Riffles cause turbulence resulting in high reflectance values. This may be made use of however, in order to map these features.

The use of ATM data for riparian habitat classification is an accurate means of determining the distribution of broad classes of vegetation. This would be an extremely useful means for examining riparian habitat change in response to channel changes if two data sets were available.

8.8. Geomorphic implications of the Tay study relating to other Scottish Rivers

Section 2.9. outlined the findings of previous work carried out on Scottish rivers. Four geomorphological characteristics of Scottish rivers relevant to the Tay study, were found. These are discussed below with reference to the River Tay study reach.

1. The Scottish rivers studied, currently exhibit a transitional pattern which lies on the braided/meandering threshold (Lewin and Weir, 1977; Werritty and Ferguson, 1980; Ferguson and Werritty, 1983). The study reach used in this research with a general channel slope of 0.002, requires a bankfull discharge of 60 m^3s^{-1} to plot in the braided region of Leopold and Wolman's braided/meandering graph. The mean annual discharge at Port-na-Craig is about 75 m^3s^{-1} and so the study reach lies just over the theoretical braided/meandering threshold. In reality, the study reach exhibits a transitional pattern with both meandering and braiding tendencies.

2. Small reaches exhibit different characteristics and respond differently to high magnitude events (McEwen, 1989; Ferguson and Werritty, 1983). Werritty and Ferguson (1980) also noted the presence of nodes along the River Feshie which remained stable and separated areas of instability. The study reach in this research exhibits distinctly stable and unstable reaches which are separated by stable nodes. Local stability appears to be largely independent of channel slope as this is relatively uniform throughout the study reach. Local controls on channel stability are apparently related to channel confinement and river bank sediment composition. This is most evident in the response of section 4. to flooding in comparison with the other sections. The river banks on both sides of this section are in the

highest risk of erosion class and between 1988 and 1993 (which encompasses two major flood events), this section showed the highest degree of braiding tendencies. In other sections where channel change occurred in response to the flood events, bank erosion was localised as a result of channel confinement in other areas. This had the result of producing a more meandering planform.

3. Major disruption of channel pattern occurs as a result of high magnitude events leading towards partially braided channel patterns. Subsequent to a flood, the channel pattern is simplified by lesser events (McEwen, 1989; Ferguson and Werritty, 1983; Werritty and Ferguson, 1980). Channel changes within the study reach have been shown to occur almost exclusively in response to major flood events. In particular, section 4 changed from a single thread pattern in 1988 to a predominantly braided pattern subsequent to the 1990 and 1993 floods. Some of the numerous mid-channel bars that resulted from these floods have become attached to the floodplain and are being recolonised by vegetation. This has had the effect of re-stabilising the section which is reverting to a single-thread channel.

4. Two studies (McEwen, 1989; Lewin and Weir, 1977) found a substantial decrease in braiding indices between circa 1900 and the 1970s. Both attribute the cause to artificial channel confinement and/or a decrease in events of high magnitude. A study by Werritty and Ferguson (1980), showed an increase in braiding index for the River Feshie during this period and the channel is not confined at this location. The findings of this research concur with those of McEwen (1989) and Lewin and Weir (1977) in that the river channel in the study reach exhibited a marked decrease in braiding index between 1899 and 1975. Evidence also suggests that this trend had begun between 1863 and 1899. It would seem

that the common factor to these case studies is channel confinement. This has wide ranging implications with respect to the nature of Scottish rivers. The five SSSI sites designated by the SNH as a result of their diversity of fauna and flora, all lie on reaches which exhibit historic instability (Gilvear, 1993). Highly active channels provide a diversity of geomorphic surfaces which in turn support a diversity of habitats. A decrease in channel activity as a result of channel confinement will decrease the availability of these diverse habitats and degrade the natural conservation value of these areas.

8.9. Recommendations for further study

This section is divided into two parts; the first is on further work that would be useful to improve the techniques developed in this study; the second part outlines further work that could be carried out on the Tay system.

8.9.1. Further work on techniques developed

The use of multi-spectral imagery to map fluvial sedimentary features on the floodplain would be an interesting area for future research. More detailed field examination would be needed to relate spectral features to the underlying stratigraphy. In addition, a study of habitat changes in relation to flood events and channel changes via the use of classified multi-date multi-spectral imagery, may provide valuable insights into the relationship between fluvial processes and vegetation dynamics. As discussed in section 8.8. the relationship between channel changes and habitat diversity is an important one with respect to the conservation value of an area.

The mapping of in-channel morphological features using black and white aerial photographs could prove valuable to channel change studies as this would allow retrospective changes to be examined. This needs a great deal more research so that the problems can be identified and where possible, overcome. A more practical case study orientated project, on the qualitative changes of in-channel morphology that can be determined over a period of time, would be useful. An examination of the wider applicability of multispectral data for mapping in-channel morphology is also needed. A classification routine which could be used on the data resulting from the bathymetric mapping technique, could be developed to classify channel asymmetry using an index such as that of Knighton (1981) or Milne (1983). This would be highly useful especially for incorporation into a model such as developed in chapter 7.

The model for the spatial mapping of erosion probabilities requires further investigation in terms of the effects of flood return periods and the consideration of intrinsic thresholds. The application of the model to large active rivers via the use of satellite data would be a worthwhile study in order to determine the success of such an exercise.

8.9.2. Further work on the River Tay system

In terms of further investigations within the study reach, an examination of the distribution of floodplain sediments would be useful. In addition, the relationship of geomorphic surfaces and vegetation composition and distribution, may provide interesting results.

Studies of sediment dynamics within the study reach have not been examined in this thesis. The detailed relationship between bar development and channel changes needs to be established by further studies as there is obviously an important relationship between these two factors.

As mentioned in section 8.9.1., an examination of habitat diversity in relation to river channel changes on the River Tay would provide important information for the determination of conservation strategies. With the increasing value of such areas for recreation purposes and the opportunities provided by set-aside policies, the return of Scottish rivers to their natural states is of increasing concern and interest.

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Appendix A.

Multispectral imagery acquired by NERC of the study area.

The imagery consisted of Daedalus AADS 1268 Airborne Thematic Mapper (ATM) multispectral imagery acquired on the 12th June 1992. The Daedalus AADS 1268 is an 11 channel digital airborne scanner recording in the 0.42 to 13.00μm region of the electromagnetic spectrum.

The wavelengths are shown in the table A.1..

Table A.1. ATM bands.

AADS 1268 Spectral Band	Wavelength (μm)
1	0.42-0.45
2	0.45-0.52
3	0.52-0.60
4	0.605-0.625
5	0.63-0.69
6	0.695-0.75
7	0.76-0.90
8	0.91-1.05
9	1.55-1.75
10	2.08-2.35
11	8.50-13.00

Data is supplied on a standard 0.5 inch nine track magnetic tape: 1600 bits per inch. The data is recorded in band interleaved by line (BIL) format.