"THE NON-TIDAL, NAVIGABLE THAMES:

A BANK EROSION MANAGEMENT STRATEGY"

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The non-tidal, navigable Thames – A Bank Erosion Management Strategy

Volume 1 to 3.

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ABSTRACT

Processes and mechanisms of bank erosion on the non-tidal, navigable River Thames were identified and investigated using site specific monitoring and extensive geomorphic surveys. As a lowland, impounded river the Thames has little potential for bank erosion associated with reach-scale morphological channel adjustments. In fact, erosion is closely related to local conditions at the bank and significant processes and mechanisms include fluvial entrainment, slumping, and weakening and weathering of *in situ* bank material. Approximately 38.5km of eroding bankline was measured (~10% of the total length). Average rates of bank erosion monitored ranged from 0.05m/yr to ~0.5m/yr. The relative contribution to bank retreat of each process or mechanism depends on local conditions such as the use of the bank, the type of bank material and the bank geometry and the type of vegetation.

Analysis of the causes of bank retreat at 147 sites along the River Thames revealed that erosion was generally influenced by a combination of factors. Navigation related activities contribute to the bank erosion at nearly all sites (~90%) but is solely responsible for erosion at only about 12%. Factors related to the use of the bank and adjacent land contribute to erosion along ~65% of the total length of eroding bank but are the sole influence at only ~5%. Channel planform and geometry contribute to ~53% of observed bank erosion, but are the sole influence at less than <1% of the erosion sites.

A review of selected of erosion control techniques applied on the River Thames suggested that solutions tend to be over-engineered and that strategies adopted were not necessarily appropriate for the causes and consequences of the bank erosion. Furthermore, whilst mitigation measures are often incorporated into the solutions, environmental enhancements are rarely included.

Assessment of the causes and consequences of erosion has led to the development of a bank erosion management strategy for the River Thames based on geomorphological and sustainability principles. The strategy is presented as a transferable tool through which to achieve sustainable river management.

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ABBREVIATIONS

d	channel depth (m)
g	gravitational acceleration ($9.81 m/s^2$)
K	von Karman's constant (0.4)
Q	discharge (m^3/s)
S	water surface slope
u	velocity measured at height z above boundary (m/s)
v	velocity (m/s)
Vmax	maximum near-bank velocity
w	width (m)
WH	wave height
z	height above boundary of velocity measurement (m)
z_o	effective roughness height (m)
°C	degrees Centigrade
ρ	density of water (1000 Kg/m^3)
τ_o	average channel shear stress (N/m^2)
τ_b	shear stress at the bank (N/m^2)
ω	specific stream power (W/m^2)
Ω	gross stream power (W/m)

ACKNOWLEDGEMENTS

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The erosion monitoring reported in Chapter Four, along with research discussed in Chapter Six, was carried out under contract to the Department of Geography, Nottingham University, as part of Phase II of a National NRA R&D Project: Bank Erosion on Navigable Waterways. The assistance of the staff and students of the Department is greatly appreciated. In particular, Prof. Colin Thorne for his supervision and assistance throughout, and also Ian Conway for his assistance with surveys, and Nick Wallestein and Eleanor Blake for their assistance with the boat wash monitoring reported in Chapter Five.

The River Thames Bank Survey (Volume II) was produced under contract to the Department of Geography, Nottingham University, and commissioned by NRA (Thames Region). Video footage used to produce the survey was filmed with assistance from Prof. Colin Thorne and NRA (Thames Region) Navigation staff. The survey is presented as part of this thesis with permission from the Regional General Manager of the Environment Agency (Thames Region).

Chapter Six also reports many examples of bank erosion management techniques that have been designed and implemented during my employment with the NRA and Environment Agency (Thames Region). I am indebted to the organisation and its employees for their inspiration and support, and could not have hoped for a more rewarding learning experience in practical UK river management than that which I have gained as an employee.

Finally, my family have supported me throughout this research. This thesis is dedicated to them.

CHAPTER ONE

INTRODUCTION

1.1 The importance of river bank erosion

River bank erosion plays an important role in channel adjustment and evolution. Processes of bank erosion are essential for river planform change and meander migration (Hooke, 1995; Lawler *et al.*, 1997) and contribute to the recovery of disturbed channels (Simon, 1989). Bank erosion and lateral channel change are also key components in floodplain renewal and the dynamics of basin sediment systems, and help to maintain ecological diversity within the floodplain (Gurnell, 1995).

However, river bank erosion can present serious problems to river managers and landowners through loss of land, the threat to floodplain structures and the increase in downstream sedimentation. In 1981 the total damages from streambank erosion in the United States were estimated at $250 million per year, while the cost of treating seriously eroding banks was estimated at $1.1 billion (USACE, 1990). In England and Wales, some £5 billion is spent annually to prevent erosion of river banks (Environment Agency, 1997).

The treatment of river bank erosion problems has tended to be *ad hoc*, often involving the use of hard engineering, irrespective of the need for structural intervention. Whilst such techniques usually eliminate the immediate symptoms of erosion (namely bank retreat) they may do so without necessarily addressing the actual cause of the erosion, which may in fact be tackled as successfully with a more environmentally sensitive, and often less costly, solution. Furthermore, implementing a solution that does not necessarily tackle the cause of the erosion could result in adverse impacts elsewhere (such as erosion downstream) that may then require action.

1.2 Understanding river bank erosion

Experience has shown us how, all too often, river management has proceeded without due consideration for the dynamic fluvial processes (eg. Sear *et al.*, 1994; Brookes, 1988). Whilst advances have been made by numerous researchers in elucidating the complexities of river bank processes (eg. Hooke, 1979; Thorne, 1982; Lawler, 1993b), uncertainty remains regarding the interaction of these processes and their contribution to bank erosion over varying spatial and temporal scales.

Causes of river bank can been divided into three categories: weakening processes, direct fluid entrainment, and mass failure (Lawler, 1992). The susceptibility of the bank to these processes depends largely on the bank material and geometry, and the type of bank vegetation. However, these influences are complex. For example, in addition to its seasonal variation, vegetation can have both positive and negative effects on bank stability. Furthermore, bank erosion is seldom the result of a single cause but is, more often, the result of the complex interaction of these processes. Consequently, the relationship between cause and effect is not always easy to establish. Hooke (1979), for example, demonstrated the importance of preparatory factors, such as precipitation, but suggested that there was no simple relationship between cause and effect.

1.3 Management of river bank erosion

Effective management of environmental systems relies on convenient access to relevant information. However, whilst many researchers have contributed to the understanding of bank erosion processes, there remains a paucity of knowledge regarding the dominant determinants of bank erosion along medium-sized and large river systems (Hooke, 1980; Lawler, 1993a).

The UK's commitment to protecting and enhancing the environment has meant that approaches adopted within river management are becoming more environmentally sensitive. Greater emphasis is being placed on understanding the interaction between river form and process in the wider context of habitat quality. Consequently, whilst unacceptable consequences of bank erosion may necessitate management intervention, the need to minimise environmental impacts, as well as reduce unnecessary costs, means that an understanding of the processes of bank erosion is essential. Without such an understanding it remains a difficult tasks to evaluate the merits of alternative approaches and develop successful erosion management strategies.

1.4 The River Thames

The River Thames is, undoubtedly, one of the region's most valuable 'natural' assets (Figure 1.1). It functions, for the majority of its length, as a navigable thoroughfare offering commercial and recreational opportunities to the thousands of craft travelling its waters each year.

The distance from the source of the Thames, at Thames Head, to its tidal limit at Teddington is approximately 230km (~143 miles). The river drains an area of ~9870km^2 above Teddington over a fall of ~93m. The Thames is, therefore, a medium-sized, lowland river, and is largely constrained by the adjacent land use, particularly along its lower reaches. The river's regime has been regulated for over a century, and a series of locks and weirs maintains navigation depths and provides the appropriate standard of flood protection for the surrounding land.

The banks of the Thames have been subject to varying degrees of pressure. As the county border between Gloucestershire and Wiltshire (see Appendix 1), the Thames has remained relatively rural in nature, exhibiting a sinuous planform with largely natural banks. Similarly, through Oxfordshire, a rural land use dominates the river corridor save for the lengths abutting the main urban centres and, to some extent, this is also true of Berkshire. As the river approaches the highly urbanised capital, natural banks have largely been replaced with hard structures, be these to provide flood defence, erosion protection, or support a particular land use.

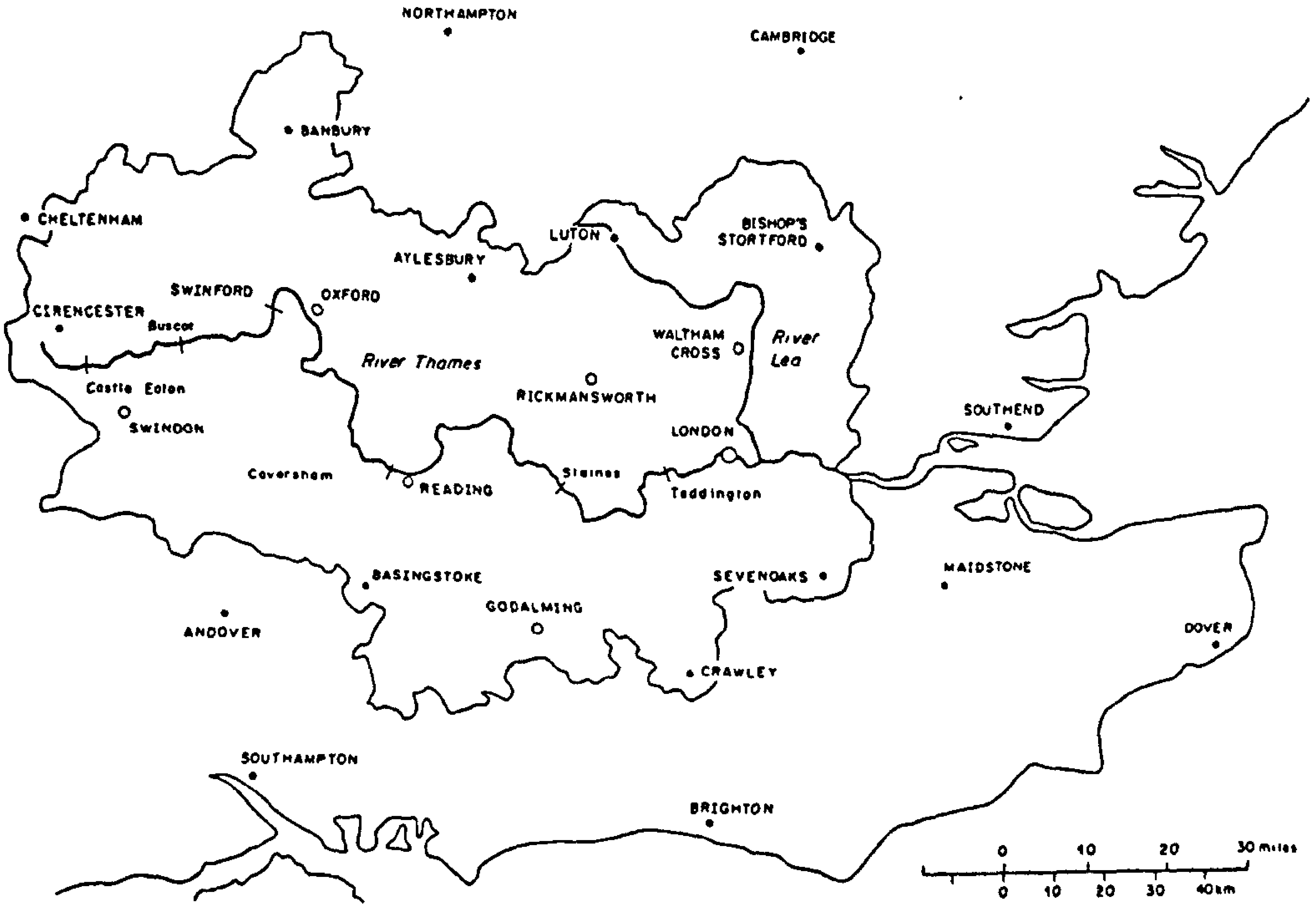


Figure 1.1 Location of the River Thames basin in southeast England, UK.

Whilst the river itself maintains a rich variety of species (NRA, undated c), the banks and the river corridor establish a valuable buffer zone between the channel and the often urbanised river valley. As a consequence, there is ample opportunity for conflicting interests between the different demands made on the river. Since the Environment Agency (Thames Region) functions as both the land drainage and the navigation authority, for the non-tidal, navigable Thames, it is tasked with ensuring that the river and its banks are managed with due regard for these functions.

Furthermore, the Environment Agency is committed to the concept of sustainable development and, under the 1991 Water Resources Act, is required to conserve and enhance the environment (HMSO, 1991). To this end, it aims to minimise the environmental impacts of its own operational activities as well as the activities of the external developers and users it regulates.

1.5 Research objectives

The overall aim of this research is to develop a bank erosion management strategy for a lowland, medium-sized, navigable river system. This research uses the non-tidal, navigable River Thames as a case study to investigate and, where possible, characterise the causes and consequences of bank erosion and, thus, develop a strategy for managing erosion.

To formulate an appropriate strategy to address a bank erosion situation, it is essential for the causes of erosion to be correctly identified, along with any other influencing factors. Only then can an appropriate solution be derived; while consideration is given to consequences of the solution prescribed. Consequently, this research aims to gain an understanding of the causes and consequences of bank erosion and their distribution along the River Thames.

The approach taken in this research was designed to (1) investigate in detail the various factors influencing erosion at a selection of specific sites along the Thames, then (2) use the knowledge gained from (1), together with hydraulic assessments and extensive survey, to characterise bank erosion along the whole river. In addition, a review of various cases where erosion management strategies have been employed along the Thames was designed to provide information with which to improve management decisions.

The various investigations and surveys undertaken as components of this research are described in Chapter Two whilst Chapter Three reviews the relevant literature relating to river bank erosion. Chapters Four, Five and Six discuss the results of the various research components which provide the rationale for the bank erosion management strategy presented in Chapter Seven.

CHAPTER TWO

APPROACH AND METHODOLOGY

2.1 Introduction

The aim of the research reported in this thesis is to develop a strategy for managing bank erosion along the non-tidal, navigable River Thames, between St. John's Lock and Teddington Lock. In line with the Environment Agency's 'pressure-state-response' approach to environmental management (Environment Agency, 1998b; 1998c) this research investigates:

- the 'pressures' on the banks of the River Thames, in terms of the causes of bank erosion;
- the 'state' of the banks of the River Thames, in terms of how the 'pressures' on the banks and the 'response' to those 'pressures' can result in a 'strain' on the environment (i.e. the consequences of erosion);
- the 'response' to those 'pressures', in terms of the actions taken to address the 'pressures' on the banks and improve the 'state' of the environment (i.e. address the consequences of erosion or reduce the 'strain').

River bank erosion is not necessarily a problem in itself, rather it is the consequences of bank erosion that may result in a 'strain' on the environment. For example, if flooding occurs as a consequence of bank erosion, then the 'strain' on the human environment could be considered highly significant. Conversely, if the only consequence of bank erosion is the loss of some part of a riparian landowner's pasture, then clearly, the 'strain' on the environment could be considered insignificant. In order to prevent the detrimental consequences of significant bank erosion it may be considered necessary to protect the river bank using an engineering structure. However, a structural 'response' will also have detrimental consequences for the conservation value of the river corridor in terms of habitat deterioration, and it is vital to take these consequences into consideration when selecting the appropriate 'response' to environmental 'pressure' due to significant bank erosion.

The geomorphological framework for bank erosion management along the River Thames addresses this issue by rationalising the risks associated with the various consequences of erosion, such as flood defence, navigation, recreation and conservation, and identifying the environmental impacts of alternative bank protection solutions. Once these steps have been completed, the framework guides decision makers towards the optimum solution which gives due weight to the risk posed by continued erosion, while avoiding unsustainable environmental deterioration through over-engineered 'responses'.

This chapter explains the study approach adopted in investigating bank erosion along the River Thames and developing a bank erosion management strategy. Section 2.2 reviews the philosophy and methodology behind the various studies undertaken as part of this research. Section 2.3 describes how these studies contribute to the development of a risk-based framework for bank erosion management based on geomorphological and sustainability principles.

2.2 Research investigations

This section reviews the philosophical and methodological aspects of the various studies and assessments undertaken in this research project. The investigations are reviewed in turn below and listed in Table 2.1.

Table 2.1 Research investigations

I	Review of literature: investigation of the factors influencing the processes and mechanisms of bank erosion
II	River bank erosion monitoring: monitoring rates and the processes and mechanisms of bank erosion at 7 sites along the River Thames
III	River bank survey: survey of bank erosion and protection along the Thames
IV	Assessment of erosion sensitivity: desk study of factors potentially influencing bank erosion along the River Thames, including stream power, channel sinuosity, boat wash and river bank characteristics
V	Assessment of bank erosion: investigation of factors influencing bank erosion at 147 sites along the River Thames
VI	Assessment of erosion management: investigation of the application of alternative erosion control strategies through consideration of numerous case studies

I Review of literature

Considerable literature exists regarding the processes and mechanisms of river bank erosion and the various factors that influence them. Chapter Three reviews this literature, placing particular emphasis on lowland, navigable rivers. Chapter Three briefly reviews the processes and mechanisms of erosion, where the factors influencing these processes and mechanisms are reviewed in terms of their influence first on flow erosivity and, second, on the erodibility of bank materials. The various factors and influences are discussed under the following headings:

- catchment characteristics
- channel planform and geometry
- river bank characteristics
- channel and bank use

II River bank erosion monitoring

In order to gain first hand experience and, thus, greater appreciation of the processes and mechanisms of erosion along the River Thames, a programme was devised to monitor bank erosion at seven sites along the river. The monitoring programme was undertaken as part of a research and development project commissioned by the National Rivers Authority (NRA). Consequently, in selecting monitoring sites the author was able to draw on the experience of NRA staff concerning the distribution of eroding banks along the river.

Lawler (1993a) recommended various techniques to measure bank erosion depending on the timescales of interest (Figure 2.1). In this study, a combination of erosion pins and repeated surveys of the bank profile was used to measure erosion over the short and intermediate timescales of interest in this research (i.e. from several weeks to approximately 1.5 years).

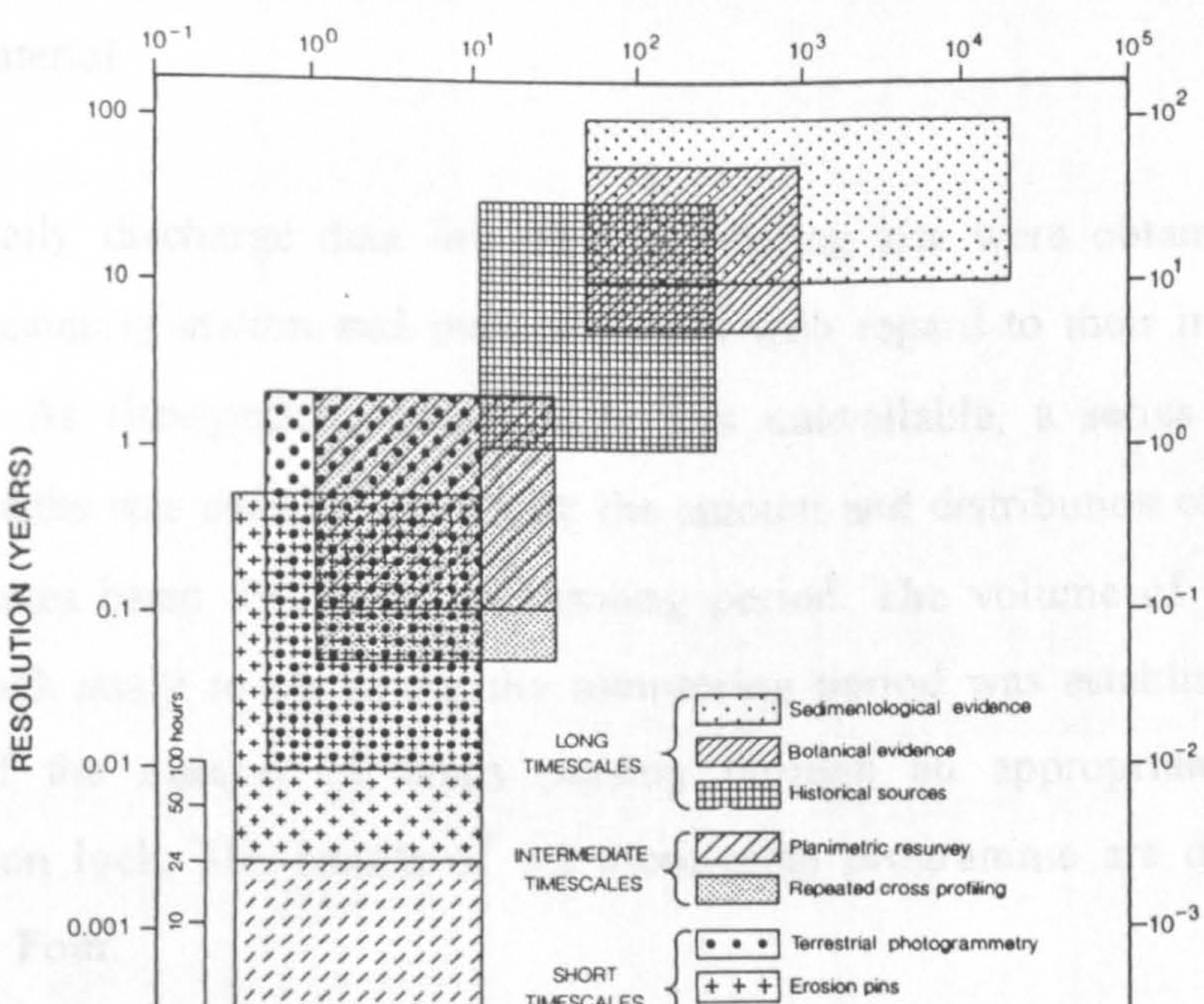


Figure 2.1 Appropriate and applicable timescales for techniques to measure rates of bank erosion and lateral channel change (Lawler, 1993a).

Initial bank profile surveys were performed at each site in 1992, when steel erosion pins were installed at various locations flush with the face of the bank. The bank profiles were resurveyed for the last time in early 1993. Between these dates, the site resurveys were carried out in spring, prior to the boating season, and in late autumn, at the end of the boating season.

Each site was visited frequently during the monitoring period and measurements were made of soil suction and shear strength in the upper and lower bank units. A standard soil tensiometer was used to measure soil suction. Peak and residual shear strengths were measured using a Pilcon shear tester. The exposed length of each erosion pin was measured and erosion since the last visit was determined unless, for example, high flow or prolific vegetation growth prevented relocation of the pin.

Soil samples were collected at each site on only one occasion during the monitoring period, and analysed to determine the geotechnical properties of the bank material.

Mean daily discharge data for each monitoring site were obtained from a nearby gauging station and were analyzed with regard to their influence on erosion. As site-specific rainfall data was unavailable, a series of rainfall hydrographs was used to investigate the amount and distribution of rainfall in the Thames basin during the monitoring period. The volume of boat traffic using each study reach during the monitoring period was established on the basis of the number of boats passing through an appropriately located navigation lock. The results of the monitoring programme are discussed in Chapter Four.

This site-specific monitoring programme was complemented by a desk-study to assess historical changes at each site. However, whilst a substantial amount of evidence exists from which to catalogue historic changes to the River

Thames, bank line recession at the monitoring sites over the last century was found to be minimal and certainly within the expected accuracy of the maps used (Hooke and Redmond, 1989; Downward, 1995). Of far greater significance were historical changes in character of the bank, established from dated paintings and photographs. Whilst no definitive and scientifically robust conclusions can be drawn from these qualitative sources, Chapter Four makes useful inferences based on this evidence.

III Thames River Bank Survey

A geomorphic survey of the banks of the River Thames was performed from St. John's to Teddington Lock. The survey was conducted primarily by videoing the entire length of both banks over a nine day period in October and November 1992. The river banks were videoed from an NRA boat using cameras mounted at the stern of the vessel but, occasional mechanical failures and outbreaks of inclement weather, produced some gaps in the coverage. Reaches with gaps in coverage were visited during the first week in August 1993, and the missing information was collected by conventional, bank-based stream reconnaissance.

The survey information was compiled to produce a map atlas illustrating various characteristics of the bank along the non-tidal, navigable River Thames. The atlas uses 1:10,000 scale Ordnance Survey maps as the base on which to delineate morphological features and riparian vegetation in the river corridor. Each 1:10,000 scale map comprises a base map showing the position of the main channel with a colour coded strip denoting the type of vegetation along the banks. A transparent overlay is used to annotate the map with symbols indicating a range of bank features.

Bank vegetation was classified into one of four categories according to the general contribution to bank stability that it provides. Further classifications were used to represent lengths of banks where vegetation was absent, where livestock had access, and where a spending beach was present. Also, a separate category was used for banks which had been structurally reinforced to allow them to withstand a high loading such as, for example, along a tow path.

The transparent overlay for each map details the type of bank protection structure present and its state of repair. The nature of the structures and the methods of survey meant that some difficulties were encountered identifying different types of protection, particularly for structures below the water surface. Nonetheless, four main categories were capable of representing the majority of structures encountered: sheet piling, brickwork, bagwork, and concrete or masonry. Additional classes were used to represent less conventional methods of bank protection, such as spiling, gabion baskets, geotextiles, wooden fishing embankments, mooring platforms and bank-side tree planting schemes.

Where possible, failures of bank protection structures were classified according to one of three categories which use the failure geometry to infer a causal process or mechanism. Water level erosion (WLE) represents failure predominantly at the normal water level. This is diagnosed as indicating that erosive flow forces generated in the channel have overcome the erosion resistance of the bank protection. Conversely, washout erosion (WOE) describes a failure behind the structure, often manifest as erosion of backfill, which is attributed to bank-side activities such as angling and mooring. The final category, surface erosion (SE), was used for protection which was intact except for degeneration of the geotextile. This occurs through erosion on the bankward-side, in contrast to WLE erosion which occurs from the channel side.

The map overlays also indicate bank-side uses. Lengths of bank where angling and grazing were evident during surveys are included, and landing stages, designated moorings and boat yards were incorporated from the

Nicholson/Ordnance Survey Guide to the River Thames (1990). A full list of the parameters recorded is given in Appendix 2.

The River Thames Bank Survey was commissioned as part of an Operational Investigation funded by Thames Region NRA (NRA, 1993). The output of the survey has been compiled as an independent document and is presented as Volume II of this thesis.

IV Assessment of erosion sensitivity

Various geomorphological assessment techniques have been applied to evaluate channel sensitivity (Brookes, 1996; Newson and Sear, 1998). Whilst some assessment techniques adopt a catchment-scale approach, such as fluvial audits (eg. Sear, 1992; NRA, 1995), others adopt a more detailed, reach-scale approach (eg. Brookes and Long, 1990; Downward, 1993).

The River Thames is impounded along the majority of its length by a series of locks and weirs, with St. John's Lock and Teddington Lock, respectively, marking the upstream and downstream limits of this study (Figure 2.2). Due to the lack of a documented history of channel change and the impoundment of the River Thames, a reach-scale approach to the sensitivity assessment was considered to be more appropriate than a catchment-scale approach.

To determine the potential for bank erosion along the River Thames, a range of approaches was applied, using information from a number of difference sources:

- an hydraulic model of the River Thames;
- channel geometry data;
- geological survey maps;
- boat traffic data;
- boat wash and flow velocity measurements;
- the River Thames Bank Survey.

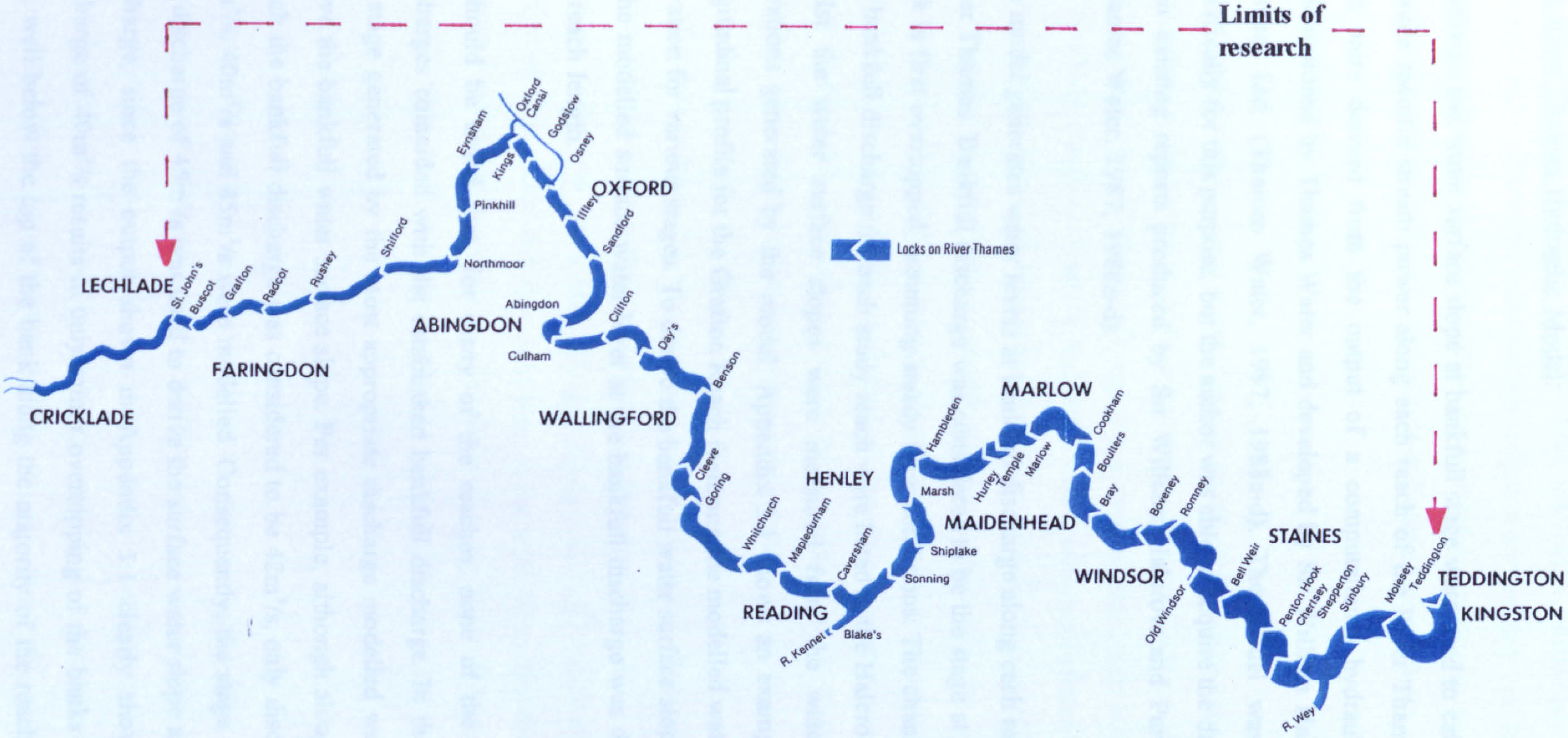


Figure 2.2 Schematic diagram illustrating the limits of this research: from St. John's Lock to Teddington Lock. (Courtesy of Environment Agency, Thames Region)

The River Thames Hydraulic Model:

Discharge and water surface slope at bankfull stage were used to calculate the average specific stream power along each reach of the River Thames. These data were derived from the output of a computational hydraulic model commissioned by Thames Water and developed by Sir William Halcrow and Partners Ltd. (Thames Water, 1987; 1988a-d). The model was not run specifically for this purpose, but the author was able to acquire the data needed from existing reports produced by Sir William Halcrow and Partners Ltd. (Thames Water, 1987; 1988a-d).

The model generates water levels at bankfull discharge along each reach of the River Thames. Bankfull discharge was considered to be the stage at which the bank is first overtopped, assuming steady flow conditions. The channel length and bankfull discharge for each study reach were listed in the Halcrow reports, whilst the water surface slopes were measured from the water surface elevations generated by the model. Appendix 3.1 shows an example of the longitudinal profile for the Grafton Reach featuring the modelled water surface elevation for various stages. To derive the bankfull water surface slope, the fall in the modelled surface water level at the bankfull discharge was divided by the reach length.

It should be noted that, for many of the reaches, none of the modelled discharges coincided with the established bankfull discharge. In these cases, the stage generated by the most appropriate discharge modelled was used to derive the bankfull water surface slope. For example, although along Grafton Reach the bankfull discharge was considered to be $42m^3/s$, only discharges of $35m^3/s$, $40m^3/s$ and $45m^3/s$ were modelled. Consequently, the stage generated at a discharge of $45m^3/s$ was used to derive the surface water slope at bankfull discharge, since the output shown in Appendix 3.1 clearly shows that a discharge of $40m^3/s$ results in only minor overtopping of the banks and is, in fact, well below the top of the bank along the majority of the reach.

Appendix 5.1 lists the data derived from the model, together with the discharges from which the water surface slopes were derived. All the values for surface water slopes derived from the modelled output and used in the analysis were within +/-5% of the established bankfull discharges.

Channel Geometry Data:

Average bankfull widths and depths for each reach of the River Thames were obtained from a review of bankfull flow events experienced in December 1952 (Thames Conservancy, 1965). Although more contemporary data would have been desirable, the River Thames hydraulic model uses cross-stream sections at intervals along the channel to defined the channel boundary conditions but gives no indication of average reach dimensions. Furthermore, the reports of the hydraulic model output provide no comprehensive information concerning the boundary conditions from which to derive reach-averaged measurements of channel geometry. For example, no width or depth data are listed in the reports and only selected cross-sections are included.

Whilst the flow regime of the Thames has changed since the 1965 publication was compiled, particularly due to the implementation of flood relief schemes, the relative changes in reach-average dimensions are believed to be insignificant. Moreover, the stream powers calculated using these data are insensitive to the depth and width. Consequently, the Thames Conservancy data (1965) were considered suitable for use in the derivation of stream power.

Geological Survey Maps:

Geological survey maps were used to derive the sinuosity along each reach of the Thames. Sinuosity compares the distance between two points along the channel centre-line to a straight line distance along the valley axis. The River Thames has a relatively complex quaternary geology, reflecting its more dynamic past. The extensive river terrace deposits which flank the main channel are remnants from a River Thames with a very different regime. Hence, in determining sinuosity, the 'valley axis' was taken to follow the contemporary alluvium, delineated on Geological Survey Maps. For example, the valley axis along Sonning Reach is shown in Appendix 3.2.

Boat Traffic Data:

Statistics on the numbers of boats passing through each lock along the Thames was obtained from the Environment Agency (Thames Region). The only use that has been made of statistics generated prior to 1990, is to establish the trend in use. The average number of craft per year passing through each lock between 1990 and 1996 has been used to evaluate the contemporary potential for boat wash to be generated along each reach.

Boat Wash and Flow Velocity Measurements:

An experiment was undertaken in August 1992 to evaluate the characteristics of boat wash generated along the River Thames. Three sites were selected at which to record boat type, position, speed, bow wave height and the maximum near-bank flow velocity generated by passage of the vessel. Sites 1 (adjacent to a wood piled bank) and 2 (a reeded bank), were located upstream of Wallingford Bridge. Site 3 (a bank protected with Nicospan), was just upstream of Goring Lock.

The parameters measured at each site were:

- Time (BST) of boat passage
- Direction of boat passage (upstream or downstream)
- Boat type (small, medium, large or barge)
- Position of craft across channel width (channel quarters 1 to 4, or middle of channel)
- Boat speed (km/hr)
- Draw down in surface water level at the bank (cm)
- Elevation in surface water level at the bank (cm)
- Maximum near-bank velocity (m/s)

Boat speed was measured by timing the time taken to traverse a known distance. The position of the craft across the channel (sailing line) was estimated by judging in which quarter of the channel width the boat travelled. The quarter of the channel width closest to the bank from which monitoring took place was assigned a position of one. The second, third and fourth quarters of the channel width, progressively moving further from the monitoring bank, were assigned positions two, three and four, respectively, and a middle position was assigned to craft travelling along the centreline of the channel.

The maximum velocity generated at a distance of 0.05m from the bank was recorded using an electromagnetic flow meter (EMF), during impact on the bank of the boat wash from each vessel. The maximum draw down and crest elevation in boat wash waves were read from a stage board positioned against the bank. Plate 2.1 shows the stage board and EMF in place during the monitoring at the wood piled bank. A discussion of the monitoring results is given in Chapter Five.

Plate 2.1
Wave board and EMF used to monitor wash characteristics.

Chapter Five also compares the bank shear stresses generated by boat wash with those generated during a flow at approximately 60% of the bankfull discharge, derived from velocity measurements taken upstream of Wallingford Bridge in September 1992. During high, in-bank flow at that time, an EMF was used to record the peak velocity at a distance of 0.05m from the bank during 10 time periods lasting 60 seconds each. The potential for erosion to result from shear stresses generated by the highest and the average of these 10 peak measurements was compared against the potential for erosion to result from shear stresses generated by boat wash along the River Thames.

The River Thames Bank Survey:

Collection of the information presented in The River Thames Bank Survey (Volume II) was described above. In order to analyse this information, selected parameters (see Appendix 2) were measured along each reach of the River Thames. Information relating to bank vegetation and bank protection was used to evaluate the potential susceptibility of the banks to erosion, as discussed in Chapter Five.

V Assessment of bank erosion

The objective of this component of the project was to a evaluate the influence of different factors on observed bank erosion along the River Thames. The key to achieving this objective was the experience and understanding gained during the compilation of The River Thames Bank Survey (Volume II). Reviewing this information identified 147 eroding sites that could be categorised according to the factors contributing to erosion. This component of the research is discussed in Chapter Five.

Since completion of The River Thames Bank Survey the author has gained a considerably greater depth of knowledge regarding the River Thames and its banks, which has also been incorporated into this analysis. Consequently, where Chapter Five identifies the factors influencing erosion at each site, this process was derived from both The River Thames Bank Survey and the additional insights gained subsequent to production of the survey. The River Thames Bank Survey was not updated with the additional information gained from the author's later experience, however, as this would have led to inconsistencies in the detail of information presented. Moreover, the resources required to update the atlas were unavailable.

The River Thames Bank Survey represents a 'snap shot' of the Thames and provides limited detailed morphological information. Nonetheless, the survey does identify many factors relevant to bank erosion and stability, including livestock access, angling and mooring. Also, as the information is presented in map form, it facilitates consideration of effects of channel geometry to some extent. Hence, in practice, determination of whether or not a length of eroding bank was influenced by a particular factor was based on judgement, supported by information extracted from the map atlas and knowledge of each site gained subsequently. For some factors, such as cattle trampling, the existence of a nearby structure, or the location of an eroding bank at the outside of a bend, a definitive determination can be made of at least some of the factors influencing bank erosion.

Factors influencing bank erosion were broadly categorised into tree groups:
- factors related to the planform and geometry of the channel;
- factors related to the use made of the river bank or adjacent land;
- factors related to navigation activities.

The length of eroding bank along the River Thames attributed to each factor (or combination of factors) was measured, to determine the extent of bankline influenced by that factor.

VI Assessment of erosion management

An assessment of the suitability and performance of different erosion control techniques was undertaken using a selection of case studies from the River Thames. The performance of these 'responses' to bank erosion was assessed against two broad criteria. First, the appropriateness of the selected bank erosion management technique was assessed in the light of the processes and mechanisms of erosion and the risks posed by the erosion. Second, the selected technique was compared to the optimum solution and its performance was evaluated with reference to the aims of environmental assessment adopted by Thames Region of the Environment Agency (NRA, 1994a). Chapter Five discusses the approach taken assessing, comparing and evaluating the bank protection solutions adopted in managing bank erosion along the River Thames.

2.3 Development of the bank erosion management strategy

In developing a bank erosion management strategy for the River Thames, the author has drawn upon various strategic approaches to environmental management recently developed by the Environment Agency and, in particular, Thames Region. Chapter Seven reviews these approaches and describes the bank erosion management strategy developed for the River Thames. This strategy uses information generated from the assessments described above to demonstrate the 'pressures-state-response' approach to erosion management and develop practical guidelines for the sustainable management of bank erosion along the River Thames.

CHAPTER THREE

FACTORS INFLUENCING RIVER BANK EROSION

3.1 Introduction

Considerable literature exists regarding processes and mechanisms of river bank erosion and the various factors that influence them (eg. Hooke, 1979; Thorne and Tovey, 1981; Thorne, 1982; Hemphill and Bramley, 1989; Lawler, 1993b; Lawler *et al.*, 1997).

River bank erosion is seldom due to a single cause but is more often the result of the complex interaction of many factors that leads to an imbalance between the forces driving erosion and those offering resistance. These factors can therefore be divided into two broad categories: those that affect the erosive forces acting on the bank material, and those that influence the geotechnical stability, or erodibility, of the bank. The aim of this chapter is to review these factors.

A discussion of factors influencing the forces driving and resisting bank erosion is best prefaced with a brief description of the processes and mechanisms of erosion (Section 3.2). Factors influencing flow velocities and fluvial entrainment are then reviewed in Section 3.3, whilst Section 3.4 reviews factors influencing bank stability and erodibility.

3.2 Processes and mechanisms of river bank erosion

Processes and mechanisms of river bank erosion fall into two main categories: the removal of material by the flow (fluvial entrainment) and weakening and weathering of the bank material. Fluvial entrainment operates in two ways: (1)

by removing particles from the surface of the bank material, known as sloughing (Leopold *et al.*, 1964) or corrasion (Hooke, 1979), and (2) by eroding material from the toe of the bank which then steepens the bank angle and results in failure of the intact bank material under gravity, or slumping. Processes of weakening and weathering act to reduce the stability of the intact bank material by reducing its strength. The mechanisms of failure in either case depend upon the geotechnical properties of the bank material.

Fluvial entrainment

For the process of fluvial entrainment to occur, the flow-induced shear stresses generated against the surface of the bank material must be greater than the resisting forces offered by the bank material. The nature of the material entrained depends on the engineering properties of the bank material.

In terms of engineering properties, banks of alluvial rivers can be considered as either cohesive, non-cohesive or composite. In the case of non-cohesive banks, fluvial entrainment removes single grains from the surface of the bank material. The critical flow velocity at which the grain is removed from the surface of the bank depends upon its weight and shape. In the case of cohesive banks, the surface of the material consists of aggregates of finer particles in the range of 1 - 10mm. These aggregates comprise strongly bonded clays, silts and sands and can behave in a similar way to coarse sands and gravels, in that entrainment is often of these larger aggregates rather than individual particles (Hooke, 1979; Thorne, 1982). Composite banks are made up of cohesive and non-cohesive materials, often in discrete layers. The coarse, non-cohesive materials are sandy gravel deposits formed from relic channel bars, whilst the finer cohesive materials are sandy silty/clays deposited during over bank flows. The engineering properties of a composite bank are, therefore, determined by the properties of the individual layers of material of which the bank is composed.

Entrainment of material from the toe of the bank can result in steepening of the bank angle and undercutting of the material above, resulting in failure of the intact bank material under gravity. Failed material deposited at the toe of the bank will either be entrained by river flows or remain at the base of the bank acting as a buttress and protecting the intact toe from further fluvial entrainment. This balance of materials at the base of the bank has been characterised as the three states of 'basal end point control, as follows:

- impeded removal: the rate of supply of failure material to the base of the bank is greater than the rate at which the material is removed by the flow. The net result is accumulation of material at the toe of the bank which reduces the bank angle and height and, therefore, increases the geotechnical stability. The supply of failure material decreases so that the bank tends towards the second state.

- unimpeded removal: the rate of the processes supplying material to the basal area and those removing it are in balance. The net result is parallel retreat of the bank, at a rate determined by the fluvial activity at the base, and no change in the overall bank geometry.

- excess basal capacity: the rate of scour at the base of the bank exceeds the rate at which material is supplied to the toe. The net result is that the bank angle and height increases. This increases the rate of supply of material to the toe so that the bank tends towards the second state.

The theory of 'basal end point control' has been used to explain cycles of bank erosion observed on the River Severn, in Wales (Thorne and Tovey, 1981) and changes in meander bend migration on the Red and the Lower Mississippi Rivers (Thorne, 1991; 1992).

Weakening and weathering

Processes of weakening and weathering fall into two groups: those that operate within the bank to reduce the strength of the bank material, and those that act upon the surface of the bank material to loosen and detach particles or aggregates.

Of particular significance to weakening and weathering is the role of soil moisture. This depends on the climatic conditions and the properties of the bank, including bank geometry and materials. In poorly drained soils, a positive pore water pressure will reduce the effective strength of the bank material. Consequently, periods of heavy rainfall or drawdown following a high river stage may reduce bank strength considerably and result in failure. Even if positive pore water pressures are not generated, the increased moisture content of the bank increases the unit weight of the material and reduces bank stability.

Cycles of wetting and drying cause shrinkage and swelling of the clay particles within the soil which leads to the development of ped fabric with desiccation cracks and reduced strength. Freezing of pore water within the bank material prises apart the soil units and loosens the structure. This weakens the soil and reduces cohesion within the bank. Needle ice can also act on the surface of the bank to dislodge particles or aggregates from the soil matrix. The movement of water through the bank can also result in the removal of particles through solution or suspension. This through flow of moisture can effectively leach the cohesive cements from the soil leaving a weaker, less cohesive bank structure. Alternatively, the seepage of water through the bank material can entrain non-cohesive sands and lead to the development of preferential drainage channels and piping, where cavities develop within the bank material and threaten its stability.

Moisture also plays a significant role in many of the processes that act upon the surface of the bank material to weaken and loosen soil particles and aggregates. For example, submergence of the surface of the soil will cause particles of air to be trapped behind the wetted layers. Air pressures cause tension between the layers which may cause failure, or slaking, along a surface normal to the bank face. Rain splash and rain wash can also weaken the soil strength and remove particles from the surface of the bank. Excess precipitation can result in runoff with sufficient slope to cause erosion of the surface of the bank material. This process is similar to the fluvial entrainment described above, except for the long-stream slope component of the river flow that acts in addition to the down-slope weight component of sheet erosion or gullying, for example. Raindrop impact can also detach soil particles and entrain them for short distances leading to down-slope creep on steep banks. Wind can act to weaken the surface of the bank material. Wind acts in a similar manner to fluid flow and can result in the removal of particles or aggregates, depending upon the wind velocity close to the boundary and the properties of the bank material. The importance of these surface processes depends largely on the extent to which the bank is protected by vegetation or other materials such as mulches.

Chemical weathering may occur within the bank material and at the surface of the bank depending upon the precise nature of the chemical processes involved. The nature and rate of such processes will depend on temperature and the chemical composition of the bank material, pore water and river flow.

Mechanical damage to the bank, for example through human or animal activities, or the impact of ice sheets and floating debris, can reduce the strength of the particles on the surface of the bank material and, thus, make them more susceptible to fluvial entrainment. Such mechanical damage results in erosion if sufficient force is applied to overcome the resistance of the bank material.

Mechanisms of bank failure

The main failure mechanisms for natural river banks are shallow slides, rotational slips, slab failures, cantilever failures and wet earth flows (NRA, 1996). The form the failure takes depends on the geotechnical properties of the bank material and the stratigraphy of the bank (Figure 3.1).

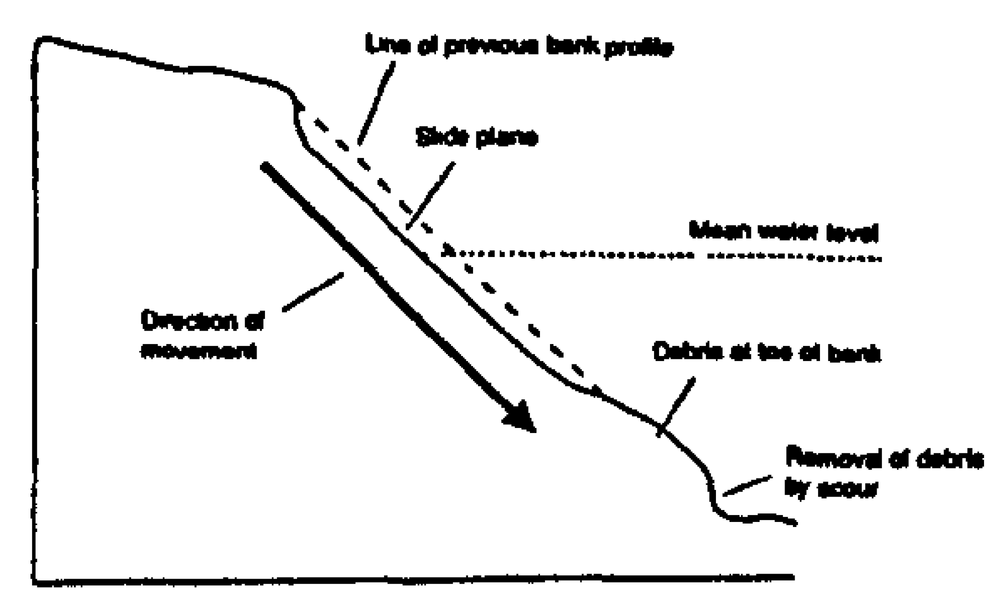
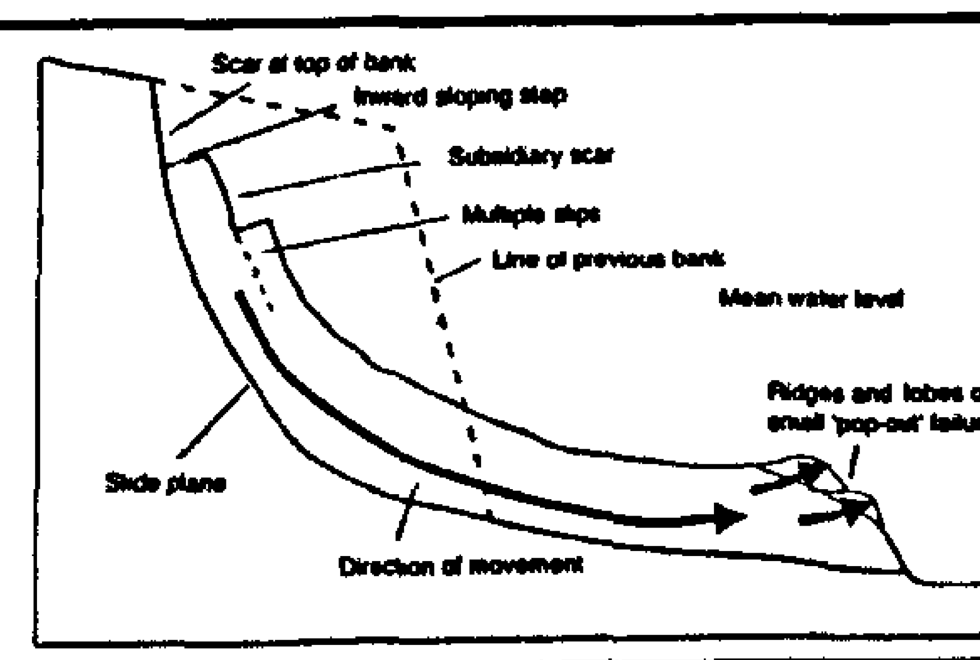
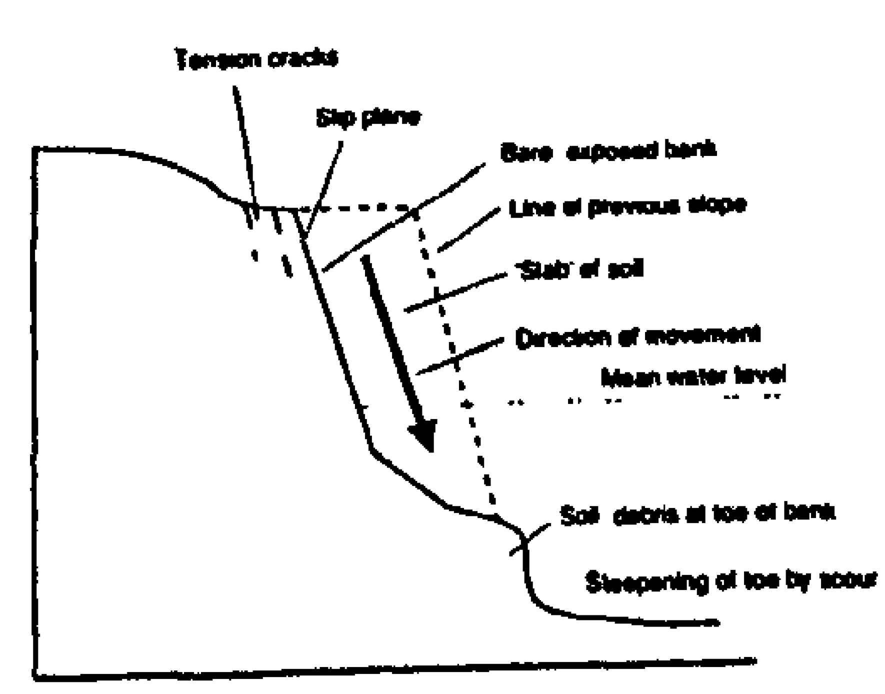
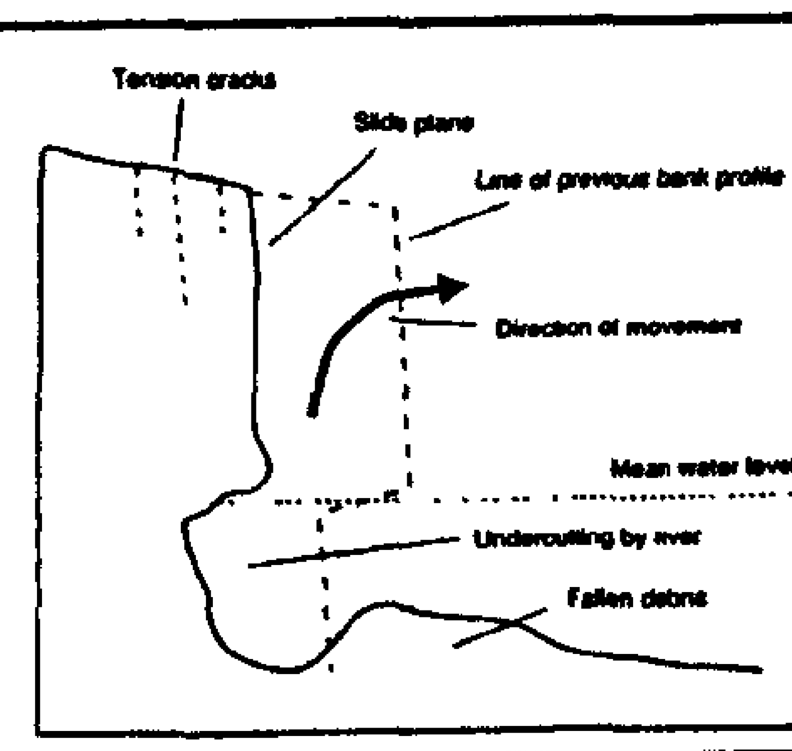
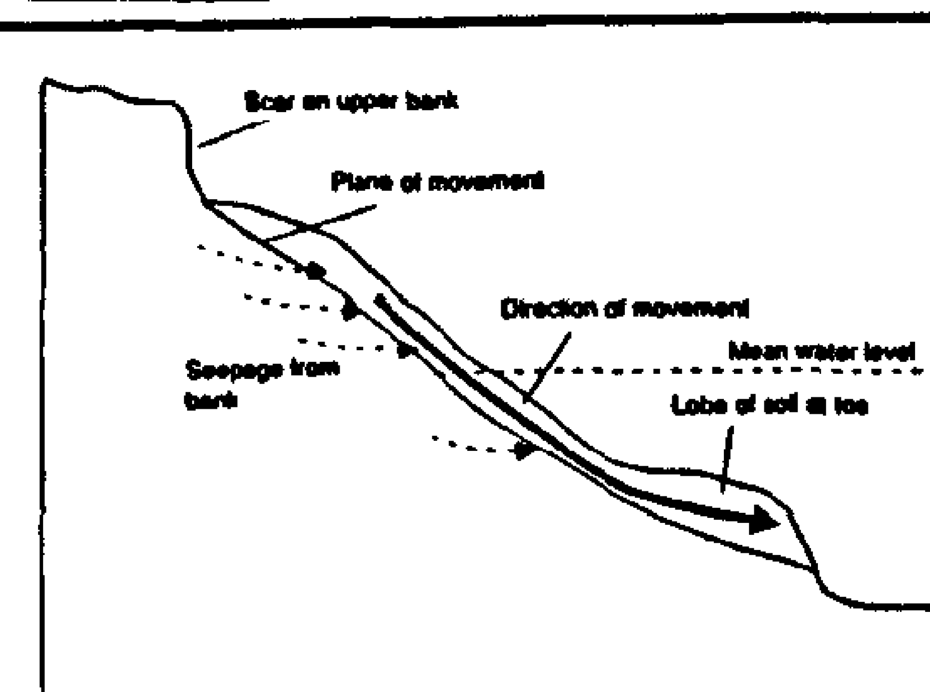
Shallow slide: movement of block of soil along a slide plane just below and parallel to the bank surface; common in bank materials of low cohesion where the bank is too steep.	
Rotational slip: deep-seated movement of soil on all or part of the bank along a curved surface; indicates severe bank instability. Slope at end of toe may be steepened or undercut by channel erosion; also associated with rapid drawdown and poor drainage of the bank material.	
Slab failure: severe failure with large volumes of soil falling as blocks/slabs into the channel, often with deep tension cracks separating the slabs from the intact bank. Associated with undercutting of the bank by flow.	
Cantilever failure: undercutting by flow causes overhanging blocks of soil to fail by toppling outwards. Failure planes develop along vertical tension cracks at the top of the slope. Common where banks are formed from a cohesive upper layer above a more easily eroded lower layer of material.	
Wet earth flow: movement of a mass of soil like a mud flow liquefaction. Occurs in banks subject to strong seepage and poor drainage. Failed materials form lobes of soil at the toe of the bank.	

Figure 3.1 Characteristics of river bank failure mechanisms (Environment Agency, 1997)

In addition to these failure mechanisms, subsurface pipes may develop where seepage is concentrated. In such pipe cavities flow velocities may be sufficient to erode particles or aggregates of bank material. The pipe may enlarge until the roof collapses leaving a semi-circular cavity at the face of the bank.

3.3 Factors influencing flow velocities and fluvial entrainment

Catchment characteristics

Of fundamental importance to river bank erosion is the magnitude and distribution of energy available to erode and transport sediment since, although flow itself is not necessary for bank failure to occur, erosion will not continue unless removal of failure material perpetuates the bank's instability.

The hydrological cycle drives the movement of water within a catchment (Figure 3.2), where a combination of processes act in a complex manner to deliver flow to the river. Key inputs to the system are precipitation and energy from the sun and wind. Hydrological processes within a catchment operate at different timescales with varying time lags between cause and effect. Flow stage can respond within hours to a single rainstorm event, whilst depleted ground water supplies may take decades to replenish. Feedback mechanisms within the system further complicate processes analysis when understanding the relationships between climate and drainage basin and channel adjustment has become increasingly important for assessing the implications of future climate change (Risbey and Entekhabi, 1996).

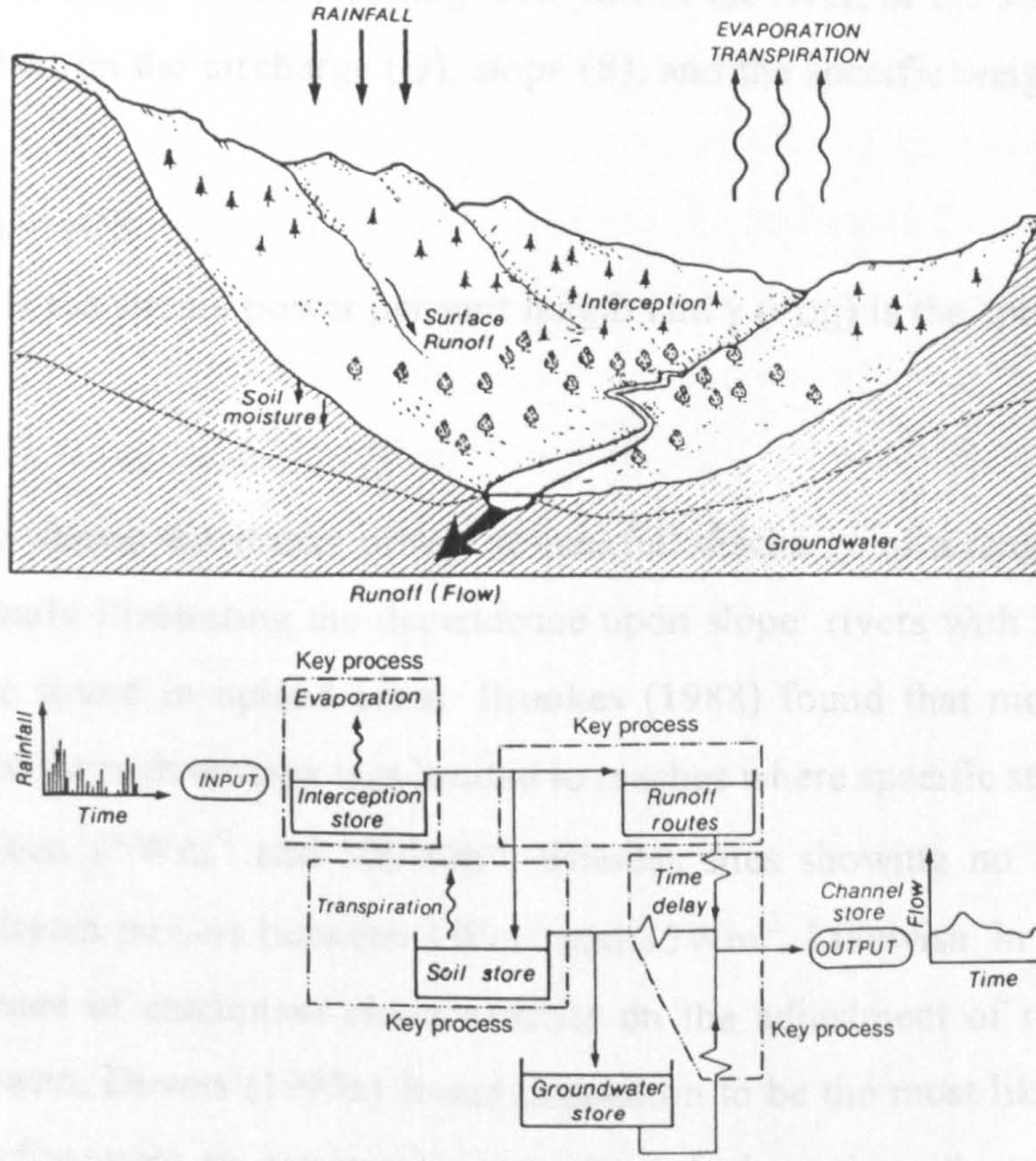


Figure 3.2 The catchment hydrological cycle (Newson, 1994)

Rumsby and Macklin (1994), for example, showed how channels and floodplains in the upland, piedmont and lowland reaches of the Tyne catchment, northern England, changed in response to abrupt short term (10 - 30 year) shifts in hydroclimate. Their analysis showed that channel degradation in the headwater tributaries and main channel reaches was associated with an increase in the frequency and magnitude of flooding (> 20 year return periods). Alternatively, accretion in trunk channels and lateral reworking of coarse sediment in headwater tributaries was associated with an increased frequency of moderate flood events (5 - 20 year return period). Their research has significant implications in the light of climate change predictions which suggest an increase in high-magnitude floods in the Tyne basin. In this case, the consequential channel incision and resulting bank failure would release large quantities of metal-contaminated alluvium into the system, with serious environmental implications.

The erosive energy of the resulting flow within the river, or the stream power, is dependent on the discharge (Q), slope (S), and the specific weight of water, so that:

$$\Omega = \gamma QS$$

where Ω is the stream power per unit length and γ (=ρg) is the specific weight of water.

Figure 3.3 shows the stream power at bankfull discharge of a range of British rivers, clearly illustrating the dependence upon slope: rivers with high stream power are found in upland areas. Brookes (1988) found that morphological adjustment through erosion was limited to reaches where specific stream power was between $25Wm^{-2}$ and $500Wm^{-2}$, whereas sites showing no erosion had specific stream powers between $1Wm^{-2}$ and $35Wm^{-2}$. Likewise, in a review of the influence of catchment characteristics on the adjustment of rivers in the Thames basin, Downs (1995a) found deposition to be the most likely form of channel adjustment in historically straightened channels with gradients less than 0.005. Similarly, Rhoads and Miller (1991) monitored channel adjustment of the Des Plaines River in Illinois, USA. They attributed the lack of any significant channel change after a 100-year flood and several bankfull flows, primarily to low stream power.

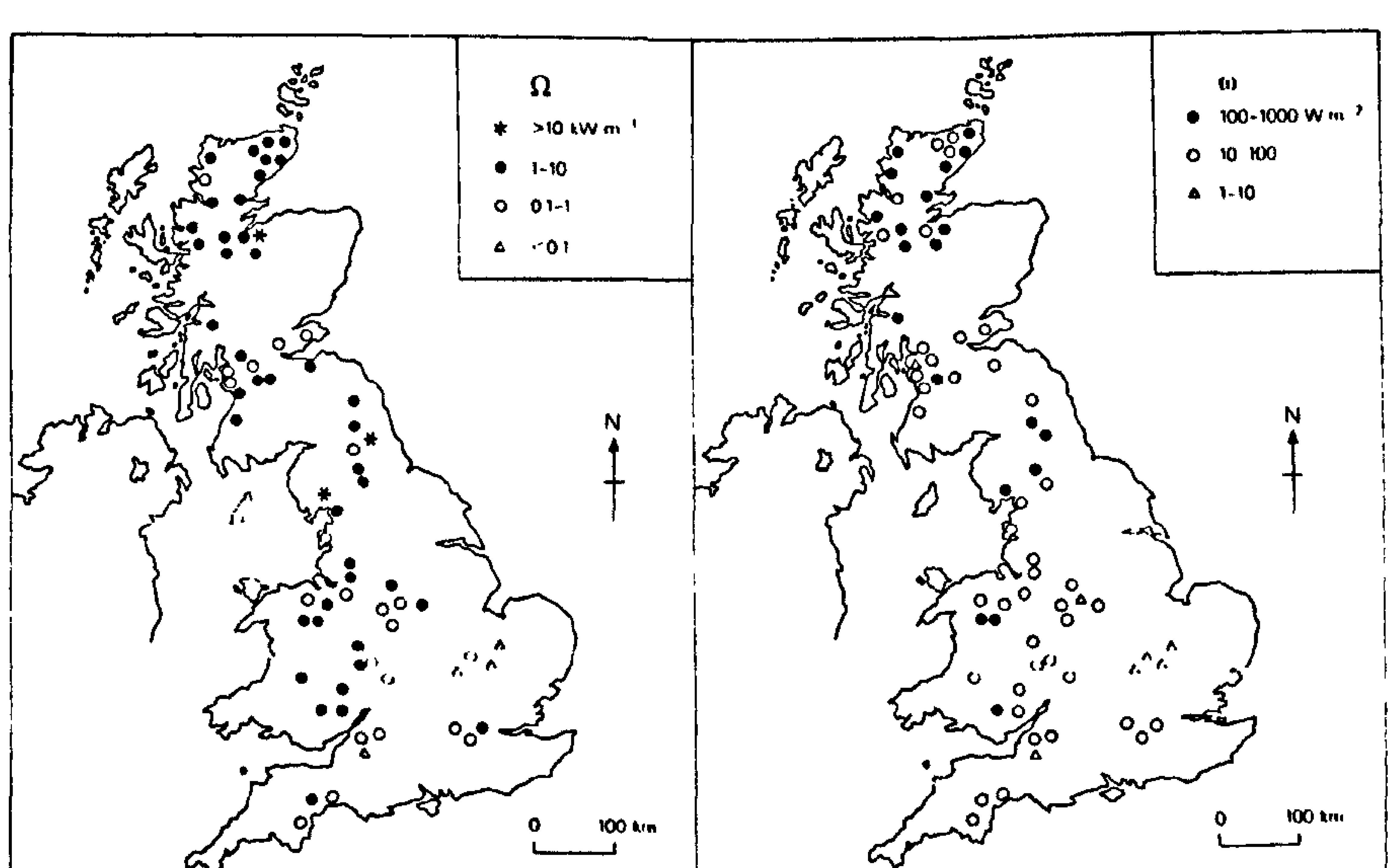


Figure 3.3 Stream power at bankfull discharge along some British rivers. Ω = power per unit channel length, ω = power per unit channel area (Ferguson, 1981)

Further energy may be supplied to the system in the form of wind. Whereas the processes of weakening and weathering due directly to wind are reviewed in Section 3.4, wind can also generate waves on the surface of the water where the fetch is sufficient, for example on the Norfolk Broads (May and Waters, 1986; Garrad and Payne, 1988). In such cases the waves act to increase the near-bank flow velocities. The resulting energy may be sufficient to overcome the resistance of the boundary material and cause river bank erosion although, in Britain, opportunities for the wind to develop sufficient fetch are limited.

Catchment characteristics such as slope, geology, soil type, land use and vegetation cover, will influence infiltration and drainage and, therefore, the resulting channel discharge and stream power. Geology, soil type and vegetation cover can also directly influence the velocity distribution and, therefore, boundary shear stress through their influence on flow resistance (see below).

Human activities have influenced processes of erosion and sedimentation for thousands of years (eg. Macklin and Lewin, 1997). Changes in land use and agricultural practices within a catchment can have profound effects on river regime and sediment supply, and the resulting channel morphology (Newson, 1980; Murgatroyd and Ternan, 1983). For example, European settlement of the Cobargo catchment in New South Wales, Australia, in around 1830, was accompanied by the clearance of vegetation and disturbance and drainage of swamps. Within decades the Cobargo catchment experienced dramatic acceleration of channel incision and bank erosion processes (Brierley and Murn, 1997).

Urban development and land drainage schemes have tended to increase runoff rates and alter the regime of rivers and their capacity to erode and transport sediment (eg. Whitlow and Gregory, 1989; Sear *et al.*, 1994). Extensive land drainage works during the last 50 years in England have typically included channel widening, deepening, embanking and re-alignment, as well as protection of the bed and banks of rivers to facilitate agricultural and urban development (Brookes, 1988). Brookes and Long (1990) suggest that up to 96% of channels in some river catchments in lowland Britain have been modified. Clearly, there is therefore considerable scope for ecological deterioration (Swales, 1982; Smith *et al.*, 1990) and for rivers to be adjusting to historic and contemporary changes in land use and river management practices (Brookes, 1992; Downs, 1995a).

Of particular significance to flow velocity is the influence of river regulation through impoundment. Controls on discharge and slope, for example through the use of dams, will alter a river's flow regime and its capacity to transport sediment. Reservoirs and dams will trap sediment loads, so that flow immediately below the impoundment will often be depleted of sediment and, therefore, cause erosion (Petts, 1977). A reduction in peak flows downstream of a dam may bring about significant morphological adjustment, depending upon the characteristics of the catchment. For example, Petts *et al.*, (1993) report a reduction in channel width and conveyance of 53% and 75%, respectively, below the Catcleugh Reservoir on the River Rede, UK. Similarly, the reduction in erosive activity and sediment transport downstream of the Vouglans reservoir on the River Ain, a tributary of the Rhône, resulted in the encroachment of the adjacent forest and the concentration of flood flows. This has intensified the tendency for the Ain to deepen its channel, resulting in the loss of spawning grounds for grayling (Bravard and Petts, 1996).

Similarly, locks and weirs will influence local flow velocities upstream and downstream. Typically, flow is slowed upstream of the structures. Operation of lock gates sends a surge of flow downstream, whilst turbulence downstream of a weir will often generate a scour pool where potential energy is expended (Thoms and Walker, 1992; 1993).

Channel planform and geometry

Since water is a viscous medium, its velocity distribution through the water column and the resulting shear at the boundary are not uniform across the channel but vary according to the resistance to flow offered by the boundary. In laminar flow, where the thin layers of fluid which make up the water column flow in parallel and do not interact with one another, the shear stress can be described by:

$$\tau = \mu \, dv/dy$$

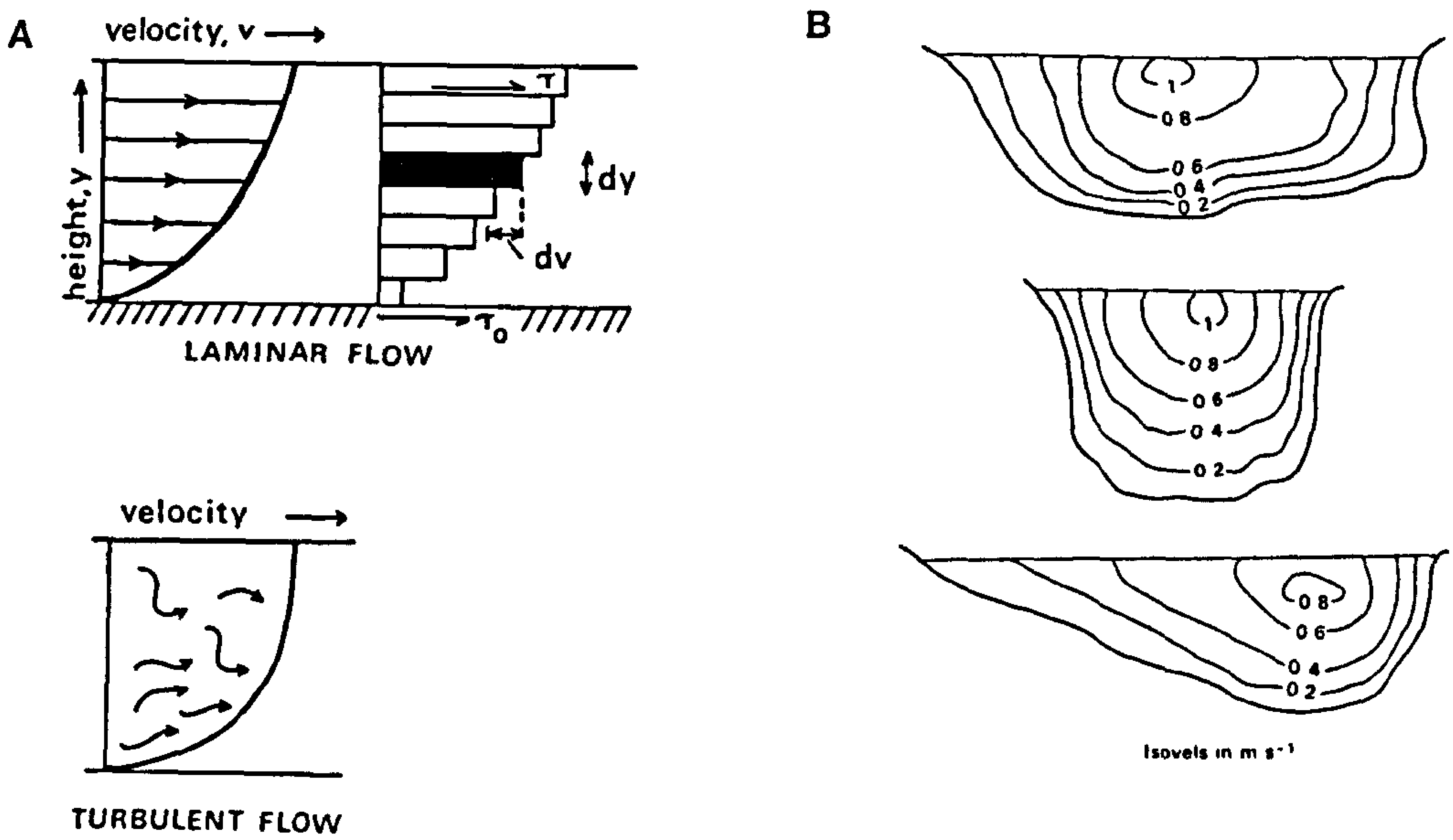
where dv/dy is the velocity gradient at depth y and μ is the viscosity of the water (see Figure 3.4).

At a critical velocity or depth when flow becomes turbulent, the interactions within the water column are no longer restricted to molecular interactions between adjacent fluid layers but extend to include the transfer of momentum through the column by large scale eddies, so that in this three dimensional flow, the shear stress becomes:

$$\tau = (\mu + \eta) \, dv/dy$$

where η is the eddy viscosity.

In reality, flow in rivers is turbulent (save for within the laminar sub-layer) and, typically in streams, the velocity across the width of the channel increases towards the centre as the frictional effect of the banks declines. Similarly, velocities in the vertical direction increase with distance from the bed and air boundaries. Consequently, channels with a high width to depth ratio (shallow, wide channels) exhibit the steepest velocity gradients and, therefore, the greatest boundary shear stress against the bed, whereas in channels with a lower width to depth ratio (deeper and narrow channels) the velocity gradient is steepest against the bank resulting in a greater tendency for bank erosion. Figure 3.4 shows the typical velocity distribution in a straight channel with a uniform cross section, and its dependence on the width and depth ratio.



A. With depth – typical velocity profiles for laminar and turbulent flow are shown.
B. At natural channel cross-sections.

Figure 3.4 Distribution of cross-channel velocity in straight and meandering channels (Knighton 1984).

Changes in boundary resistance will effect the rate of change in velocity close to the boundary and, therefore the shear stress exerted on the boundary materials. The resistance offered by the boundary also includes that due to the roughness of the boundary material and any bedforms which also provide resistance to flow. Consequently, a channel with boulders lining the bed will offer greater grain resistance than a sand bed river, with the size and sorting of sediments the determining factors. Features that develop within the bed material, such as dunes, ripples and antidunes in sand bed rivers (Bridge and Jarvis, 1977), and pools and riffles in gravel bed rivers, add to the flow resistance (Simons and Richardson, 1966; Richards, 1976). The precise interactions between bed geometry and resistance remain poorly defined because of the dependence of resistance on form and *vice versa.*

Obstructions to flow such as bridges, locks, weirs and local bank irregularities, which cause perturbations in the boundary resistance or channel alignment, will result in local changes in the velocity distribution and, thus, boundary shear stress.

Channel planform has been widely used to classify rivers (Leopold and Wolman, 1957; Schumm, 1977; Richards, 1982; Thorne, 1997; Alabyan and Chalov, 1998) and the controls on channel pattern are the most studied aspects of changing river channels (Hooke, 1995). The shape of a channel offers additional resistance to flow and adjusts to the input of water and sediment from upstream. This adjustment may involve erosion and deposition, depending on the energy available (stream power), the input of sediment and the ability of the bed and banks to resist erosion. Where the banks of a river are more resistant to erosion than the bed, lateral erosion is more likely than incision, and *vice versa.* As a river flows downstream its discharge generally increases, whereas the slope decreases. Stream power, therefore, tends to reach a peak along the middle reaches of a river. Associated with this energy change, and sediment input from upstream, is a change in river pattern. A straight channel in the headwaters progressively develops into a meandering and then, with sufficient sediment and stream power, a braided system.

Associated with river channel adjustment is the concept of a dominant channel-forming discharge. This is the time-averaged discharge necessary to develop the existing channel morphology. The 'bankfull' discharge is considered to be the 'dominant discharge' (Ackers and Charlton, 1970; Carling, 1988), which often equates to the flow that occurs on average once or twice a year (Pizzuto, 1988).

Flow through curved channels and the dynamics of river meandering have received considerable attention. Callander (1978) reviewed much of the theories of secondary currents, flow separation and sediment transport, drawing from various field and laboratory studies and theoretical analyses. As flow enters a meander bend the centrifugal forces skew the mainstream velocity profile to generate cross-stream, or secondary, currents. The depth, or stage, of flow and bank angle (see 'river bank characteristics', below) are critical in determining the development of strong secondary currents at bend apices and the existence of a cell of reverse rotation close to the outer bank (Bathurst *et* *al.*, 1979; Hey and Thorne, 1979; Thompson, 1986; Whiting, 1997). Other factors also influence the velocity distribution at a meander bend, including sediment transport, the bend radius of curvature and the change in curvature through the bend, the shape of the channel cross section and bank angle and the channel pattern on the approach to the bend (Hooke, 1975; 1995; Odgaard, 1982; Dietrich and Smith, 1983; Thompson, 1986; Begin, 1987; Odgaard and Bergs, 1988; Chen and Shen, 1988; Pizzuto and Meckelnburg, 1989). Many of these characteristics have been used to develop empirical relationships to predict velocities at the toe of the outer bank (eg. Odgaard, 1982; Pizzuto and Meckelnburg, 1989; Reed, 1990).

An asymmetrical channel cross section (Figure 3.4) is typical of a meander apex where the core of maximum velocity, or thalweg, is located towards the outer bank. At the bend apex, the development of secondary flow and the distortion of the velocity profile and distribution of boundary shear stress promotes accelerated bank erosion along the outside of the bend and migration of the meander (Lapointe and Carson, 1986; Thompson, 1986). Pizzuto and Meckelnburg (1989) found a linear relationship between rates of bend migration on the Brandywine Creek, Pennsylvania, and the near-bank velocity. Hooke (1979; 1980) monitored erosion at various locations, including meander bends, on a number of rivers in Devon, and measured mean rates ranging from 0.08m to 1.18m per year and a maximum rate of 2.5m per year. These rates are comparable to rates measured elsewhere in the British Isles (Hooke, 1980).

The presence of islands within the main channel also influences the velocity distribution because the relative boundary resistance increases as the flow divides into two channels. The flows reconverge downstream in a complex hydrodynamic environment governed by the flow hydraulics within each of the converging channels and boundary conditions of the downstream channel (Rhoads and Kenworthy, 1998). Flow converging downstream of asymmetric islands can result in deflection of the main stream flow towards one side of the channel where it impinges on the bank in a similar manner to the skewing of the mainstream velocity around a meander bend.

Although suspended sediment within the flow is dependent on the geology and soils of the catchment, as well as land and channel use and vegetation cover, its influence on flow velocities is best placed alongside references to flow resistance since it acts to dampen turbulence, in a similar way to channel vegetation (see below), and so reduce resistance. Vanoni and Nomicos (1960) demonstrated that, relative to pure water, suspended sediment concentrations of $3.64kg/m^3$ and $8.08kg/m^3$ decreased friction by 5% and 28%, respectively. However, it is generally accepted that the influence of suspended sediment on flow resistance is relatively small.

River bank characteristics

The geometry of the bank influences the velocity distribution of flow adjacent to the bank and, therefore, the boundary shear stress. Consequently, for equivalent depths of flow, a steep bank will typically generate higher shear stresses than a sloping bank. Flow velocity increases with depth so that, whereas flow velocities adjacent to low banks will be limited, velocities will be higher in the deeper waters adjacent to higher banks (see Figure 3.4).

The angle of the bank affects the drainage of moisture from the bank material, although this is also governed by the permeability of the bank materials (see Section 3.4). The affect of bank angle on runoff over the face of the bank is, included as a weakening process in Section 3.4.

The slope of the bank has an indirect influence upon flow velocities through its effect upon vegetation. For healthy vegetation colonisation the slope of the bank should be 2:1 at most (Bowie, 1982). Poor vegetation offers little resistance to flow, whereas a healthy covering of homogenous vegetation can provide considerable protection from erosion.

Channel and bank vegetation, including leaf litter can increase the boundary roughness and dampen turbulence. The influence of vegetation on flow velocities depends upon species, health, location and density. Vegetation in front of the bank is effective in reducing the energy of waves reaching the bank (Bonham, 1980; 1983), and in-channel vegetation can effectively dampen turbulence (Kobayashi, *et al.*, 1993). Dense vegetation or leaf litter on the face of the bank can also offer additional resistance to flow, with short, flexible bank vegetation generating less resistance than longer, woody stems (Coppin and Richards, 1990). Vegetation generally reduces the velocity gradient at the surface of the bank and, therefore, reduces the potential for erosion. This reduction in velocity can result in sediment deposition. However, a non-uniform vegetation cover can cause turbulence, or flow deflection (Thorne, 1990). Deflection of flow towards the bank can result in its erosion (Hooke and Harvey, 1983; Davis and Gregory, 1994), particularly where there is little vegetation to protect the surface.

Dead and dormant vegetation, including woody debris, can have a similar effect on flow velocities (Thorne, 1990), although Parsons (1963) found bermuda grass was most effective in increasing boundary roughness when it was young, sturdy and resilient, with effectiveness gradually declining until late winter and early spring when it was least effective. In addition to its influence on local velocities close to the bank, debris can accumulate across a river and effectively dam the flow. Gregory (1992) described the change in flow regime along Highland Water, New Forest, following removal of a series of debris dams. Average velocities along Highland Water increased to 2-3 times those prior to dam removal. Likewise, sediment transport increased and there was an increase in localised bank erosion. The influence of the debris dams on slope and, therefore, stream power was limited to moderate flows, and the change in regime for peak discharges was not significant since the debris dams were drowned out.

The influence of vegetation upon erosion is, therefore, not constant. Masterman and Thorne (1992) demonstrated the seasonality of this influence and also linked the effect of flow geometry. Their analysis of resistance predicted that flexible grass species grown to a height of 1.6m reduce discharge capacity by less than 10% in channels with width-depth ratios greater than 16. The reduction in discharge capacity due to vegetated banks increases as width-depth ratio decreases, reflecting the increase in relative boundary roughness in a narrower channel.

Vegetation can also influence flow velocities indirectly where good growth prohibits or reduces access to the banks. Trees overhanging the bank or extending some distance into the channel will deter boats from passing close to the river margins and so reduce the impact of boat wash on the bank (see 'Channel and bank use', below). However, shading of the channel by overhanging vegetation will reduce the growth of bank vegetation or aquatic and semi-aquatic plant species (Swales, 1982), thereby limiting the extent to which flow velocities can be reduced.

Channel and bank use

Similarly to wind generated waves, the wash generated from boats affects flow velocities close to the bank. Boat movement generates two distinct types of waves: bow waves, travelling out from the bow of the boat and impacting the bank at an oblique angle, are believed to be responsible for more bank erosion than the transverse stern waves which are produced behind the boat and run parallel to the bank (Figure 3.5). The height of the bow wave diminishes with distance from the vessel and is dependent on other factors such as hull design, flow depth and the velocity of the craft relative to the flow (May and Waters, 1986; PIANC, 1987; Hemphill and Bramley, 1989).

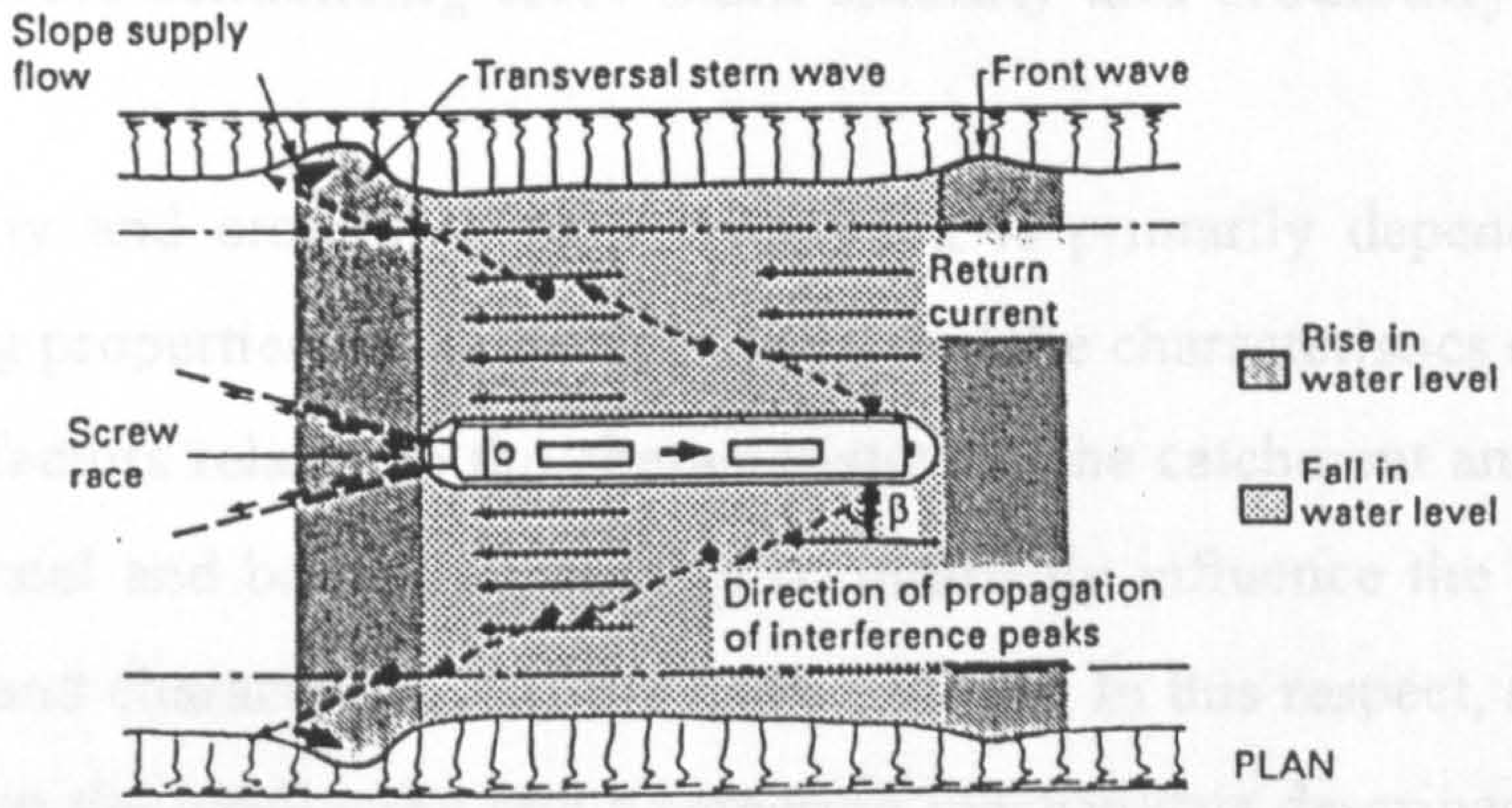


Figure 3.5 Components of ship induced water motion (PIANC, 1987)

In addition, propeller action can generate high flow velocities. Although, in comparison to bow or transverse stern waves, this has little direct influence on the banks during when cruising it can result in bank erosion when starting from a stationary position or manoeuvring close to the bank. Wash from propellers can increase water turbidity as river sediments are re-suspended (Mazumder *et al.,* 1993). The consequent reduction in water quality on Broadland rivers in the UK has been implicated as a contributory factor to the decline of aquatic plants which provide the bank with protection from erosion (Garrad and Hey, 1987).

The increase in boat traffic over the last few decades along the River Thames and the Norfolk Broads has been associated with increased bank erosion (Bonham, 1980; Payne and Hey, 1982; May and Waters, 1986; Garrad and Hey, 1988). Similarly along the Ohio River, it has been suggested that an increase in boat traffic and the operation of navigation-aid structures is responsible for increased bank erosion. However, whereas boat traffic increased significantly along the Ohio River between 1977 and 1983, the banks appeared less eroded in 1983 than in 1977 and, following extensive surveys, the primary erosion mechanisms were identified as scour during floods and failure due to drawdown following flood recession (Hagerty *et al.*, 1981; Hagerty and Hagerty, 1989).

3.4 Factors influencing river bank stability and erodibility

The stability and erodibility of a river bank is primarily dependent on the engineering properties of the bank material and the characteristics of the bank. However, factors related to the characteristics of the catchment and man's use of the channel and banks can directly or indirectly influence the engineering properties and characteristics of the bank material. In this respect, such factors contribute to the weakening and weathering mechanisms described in Section 3.2.

Catchment characteristics

Whereas precipitation drives the hydrological cycle, rain falling directly on a river bank can remove particles or aggregates from the surface of the bank material (Richards, 1982). Precipitation in excess of infiltration results in runoff which can also lead to erosion through processes such as sheet erosion and gullying (Kirkby and Morgan, 1980). Infiltration is governed by the permeability and drainage characteristics of the catchment, including geology, soils, vegetation and land use.

The engineering properties of the bank material, which are of fundamental importance to the stability of a river bank, are largely governed by the catchment geology and the way in which the contemporary river system has evolved through geological timescales. Indeed, investigation of historic alluvial deposits is now providing more evidence of events that have shaped the evolution of modern landscapes (eg. Hooke *et al.*, 1990; Brown and Keough, 1992; Taylor and Lewin, 1996; Newson, 1997). The influence of the engineering properties of the bank material on bank erodibility is discussed in "River bank characteristics", below.

Where there is sufficient fetch, wind can remove particles or aggregates from the surface of the bank material in a similar manner to the way in which flow initiates the motion of particles on the river bed (Gillette *et al.*, 1996). Topography and climate influence the stability and erodibility of river banks in several other ways. Perhaps one of the most obvious influences is on the moisture content of the bank material and the resulting influence on unit weight and cohesive properties of the bank material. A further influence upon bank stability and erodibility is that of temperature. Temperature, along with pressure, affects the growth of vegetation and the movement of moisture within the bank through evaporation and evapotranspiration. These influences alter the characteristics of the bank material and are, therefore, discussed alongside the influence of other river bank characteristics below.

River bank characteristics

Of fundamental importance to the stability of a river bank are the geotechnical properties of the bank material, the bank geometry and vegetation cover and the moisture conditions within the bank. Depending on the nature of the bank material, the banks of an alluvial river can be described as either cohesive, non-cohesive or, a combination of the two, composite. Cohesive banks generally tend to be more stable with respect to erosion, with clays and organic matter and plant roots adding both strength and flexibility to the matrix. The nature of cohesion is complex and, among other factors, depends on the type of clay and the calcium and sodium ion concentrations of the soil pore water relative to river water (Arulanandan, 1980; Grissinger, 1982). Conversely, sand and gravel offer no cohesion and may result in the bank being easily eroded, particularly if concentrated in isolated lenses in the bank.

The velocity of runoff over the face of the bank will clearly increase with bank slope and, thus, increase the potential for weakening and entrainment of particles on the surface of the bank. The bank's height and slope will also determine the geotechnical stability of the bank and, along with engineering properties and vegetation cover, will influence the drainage characteristics and the pressures within the bank relative to the atmosphere and the main flow.

In reality, it is often difficult to separate the effects of bank geometry, soil properties and vegetation upon bank stability. For example, Thorne and Lewin (1979) observed bank retreat by undercutting and over steepening, followed by slumping, and found the rate of bank retreat on the River Severn varied significantly depending upon the properties of the bank materials. The rate of retreat of the lower part of a bank, which comprised sand, gravel and cobbles, was an order of magnitude higher than the rate of retreat of the upper part of the bank, which was cohesive. Similarly, Okagbue and Abam (1986) and Grissinger (1982) observed erosion of the non-cohesive lower bank with undercutting and subsequent failure of the upper cohesive bank. Okagbue and Abam (1986) and Abam (1993) also attributed bank failure to the drawdown of soil moisture after flood recession. Springer *et al.* (1985) found that bank stability was most sensitive to depth of water present in tension cracks behind the face of the bank. Again, observations included the presence of a non-cohesive lower bank, that acted as a slip plane, and seepage of water through the bank. Okagbue and Abam (1986) also observed seepage of water through the more permeable, non-cohesive lower layers of the bank due to increased infiltration behind the bank. Similarly, Hagerty *et al.* (1981) identified seepage of water from the face of the bank following flood recession as a primary mechanism of erosion. This was linked to high precipitation and low temperatures. In this case, the saturated frozen bank remained stable until higher temperatures melted the soil moisture, sending water and soil flowing from the banks.

Hooke's (1979) analysis indicated that bank retreat was more strongly correlated with antecedent rainfall than with flood magnitude, reflecting the influence of soil moisture conditions on bank stability. Likewise, massive bank failures along the lower Obion River, West Tennessee, in 1988 were primarily attributed to a combination of high soil moisture content and low river stage against a background of substantial recent bank accretion (Wolfe and Bryan, 1991). Analysis suggested that removal of the accreted bank material would have stabilised the bank, even under the rapid drawdown that triggered the 1988 failures (Wolfe and Bryan, 1991). This further demonstrates the importance of moisture conditions and bank geometry in determining overall bank stability.

The geometry of a bank influences vegetation in several ways and may offer an environment in which only adapted plant species can survive. The slope of the bank is particularly important because roots tend to grow downwards and require sufficient anchorage for long-term success. A slope of no more than 2:1 is recommended for successful colonisation (Bowie, 1982). The height of the bank in relation to river level is also critical and different plant species are adapted to tolerate different hydrological regimes (Coppin and Richards, 1990). As discussed in Section 3.3, the reduction of flow velocities by bank vegetation can create a depositional environment resulting in bed accretion and, thus, lowering of the bank height and increased bank stability, or floodplain accretion, where the bank height will be increased and stability reduced.

Interactions between vegetation and bank material are initiated primarily within the root zone and the stabilizing effect of roots will, therefore, only operate on the bank to the depth of the roots (Thorne, 1990). Vegetation facilitates the movement of water, air and nutrients within the soil horizons, improving the structure of the soil and, through decay, provides essential organic matter to support the organisms that play a vital role in maintaining the soil structure.

Vegetation can either increase or decrease river bank stability, depending upon the type of vegetation and the bank material and geometry (Thorne and Osman, 1988; Thorne, 1990). Dead root voids can act as preferential drainage passages and lead to weakening of the bank material, but live roots generally have a stabilising effect on river banks. Exceptions to this are the loading of trees and the susceptibility of trees to wind throw. Trees growing at the bank edge can be exposed to sufficient air turbulence to be completely uprooted, often taking several metres of bank material with them. Trees appear to be more susceptible to wind throw when grown in isolation or, as is often seen along managed reaches, where the trees are spaced several metres apart but between which there is a sufficient distance over which wind velocities can accumulate. Trees lining river banks are often pollarded to reduce this susceptibility.

The influence of vegetation on bank erosion can be significant. For example, Odgaard (1987) identified 87 eroding bends along a 230km length of the Des Moines River, Iowa, most of which had little or no vegetation and <10% were flanked by mature trees. Cutbank erosion at bends was 2m-4m per year. On bends flanked by mature trees the erodibility was lower by a factor of about 2 than on bends where there were no mature trees. The influence of root structure on bank strength is dependent on the species of plant. For example, Pizzuto and Meckelnburg (1989) found that rates of bank erosion were reduced where the density of silver maples (*Acer saccharinum)* is high, whereas boxelder (*Acer negundo)* and white ash (*Fraxinus americana)* did not influence rates of bank migration.

Low temperatures and light intensity can inhibit vegetation growth and, thus, its potential stabilising influence on the bank (Swales, 1982). Furthermore, freezing temperatures increase the volume of the water within the bank, causing the soil particles to fracture from within and flake off or erode. Under suitable conditions, needle ice can also form at the surface of the bank material and result in removal of particles or aggregates through a number of mechanisms (Lawler, 1993b). Whereas many researchers have suggested that the contribution to bank erosion from frost action is not significant (eg. Hooke, 1979; Simons and Li, 1982), Lawler (1993b) attributed 32% - 43% of the sediment yield from bank erosion measured over a 2.25 year period to needle ice. Vegetation cover alters the microclimate. For example, average temperatures increased by 3.7°C in a forested basin compared to a moorland basin, making the influence of frost on forested stream banks half as frequent and reducing erosion accordingly (Stott, 1997).

Vegetation can also protect a bank from mechanical damage by ice sheets, boat impact, floating debris and livestock and pedestrian traffic. Vegetation not only prevents shearing of the surface of the bank material, but it can also effectively discourage access to the bank and, therefore, reduce the opportunity for mechanical damage from pedestrians or livestock (see 'Channel and bank use', below).

The importance of riparian vegetation to channel stability has been well recognised (Coppin and Richards, 1990; Gurnell, 1995). Vegetated channels tend to be narrower, deeper and less steep than their unvegetated counterparts. Millar and Quick (1993) demonstrated that with well-developed bank vegetation, channel widths, depths and slopes were in the order of 0.6, 1.4 and 0.9 times greater than their respective unvegetated channels. Vegetation therefore plays a vital role in channel adjustment and is often used as an indicator of channel change (Simon, 1989; Blaschkie, 1990; Gregory, 1992).

Land, channel and bank use

The management and use of rivers can have considerable implications for bank stability. Operations such as regulation and engineering works, that alter the regime of the river (as discussed in Section 3.3), also have implications for the moisture regime within the bank material and, thus, its stability. Prolonged flood peaks will extend the period in which the bank material is saturated, whilst rapid drawdown following flood recession will tend to induce positive pressures in the bank material (as discussed above).

More directly, man's use of the river can result in mechanical damage to the banks. For example, the use of pegs hammered into the bank to secure boats to their moorings may weaken the bank material and create holes in the bank which can expand as a result of preferential drainage from runoff. Navigating close to the river bank can cause scour from the propeller and mechanical damage if the propeller or vessel impacts the bank. Erosion such as this is likely where boats moor at unprotected banks, and boats operating close to river banks may have significant site-specific impacts (Hagerty *et al.*, 1981).

Pedestrian access can destroy vegetation, compact soil and result in significant local bank erosion. Angling is popular along many rivers and access to the water's edge is often restricted to a number of well defined sites (swims) which receive considerable pressure from constant use. At these locations the bank vegetation is typically diminished and the soil compacted. Walking alongside the river bank, and general recreational use of the river, may also result in some vegetation damage and soil erosion, especially where there is particularly high usage.

River banks provide nesting and shelter for birds and mammals. Burrowing animals can threaten bank stability if cavities excavated weaken the intact material sufficiently to cause its failure. Cavities can also experience a concentration of flow velocities which can further increase their size. In addition, livestock and, to a lesser extent, domestic animals can increase loading on the bank and cause considerable mechanical damage. This is most evident where cattle access the water's edge at a particular site and, in doing so, trample the bank destroying vegetation and damaged the soil (Trimble, 1988; 1994).

Local agricultural practices and maintenance regimes influence bank stability in three ways: (1) through their influence on bank vegetation, as discussed above; (2) through their direct increase in the unit weight of the bank material; (3) through their influence on soil cohesion, since ploughing up to the edge of the bank will tend to decrease cohesion within the plough layer. Management practices are tailored to avoid negative environmental effects (Environment

Agency, 1998g) and buffer strips are advocated along river corridors (Environment Agency, undated a).

CHAPTER FOUR

RIVER BANK EROSION MONITORING

4.1 Introduction

The last chapter reviewed the processes and mechanisms of river bank erosion and the factors influencing fluvial entrainment and bank stability. This chapter aims to assess these processes and mechanisms and those factors operating to influence bank erosion on the non-tidal, navigable River Thames.

A programme was devised to monitor erosion rates at seven sites established along the River Thames (Table 4.1). Details of the methodology behind the monitoring programme were discussed in Chapter Two. The results from the monitoring are discussed for each site in turn and then reviewed in Section 4.9.

Mean daily discharge data considered representative of the monitoring sites were collected and analyzed with regard to their influence on erosion. These data are presented in Appendix 4.5. There are no rainfall gauges within close proximity to any of the erosion monitoring sites, therefore, no site specific data were available with which to analyze the influence of rainfall on erosion. However, data representative of rainfall within the Thames basin are included in Appendix 4.5 to provide some indication of the magnitude and frequency of rainfall events near to the erosion monitoring sites.

Details of boat traffic during the monitoring period were obtained for each site. A record of the number of boats through an appropriately located lock was used as an estimate of boat traffic along a study reach. Appendix 4.6 compares the traffic at each of the sites.

Table 4.1 Seven bank erosion monitoring sites on the River Thames.

Reach	Monitoring site
Buscot Reach	St.John's
Cleeve Reach	Upper Wallingford
Cleeve Reach	Lower Wallingford
Goring Reach	Goring
Chertsey Reach	Laleham
Shepperton Reach	Upper Chertsey
Shepperton Reach	Lower Chertsey

The selection of monitoring sites relied on staff from the land drainage authority (National Rivers Authority, NRA, now Environment Agency) to identify sites that would be suitable for monitoring erosion rates. The degree of monitoring varied between sites and was particularly dependent on accessibility.

An initial survey of each site was carried out early 1992 when steel erosion pins were installed flush with the face of the bank at various locations. Final surveys of each site were repeated in early 1993. In addition, surveys were carried out prior to the boating season and in late autumn. Each site was visited at intervals during the monitoring period when soil suction and shear strength measurements at the upper and lower banks were recorded, along with the length of exposure at each erosion pin since the last visit.

The relative locations of the seven monitoring sites along the River Thames are shown in Figure 4.1, with more detail of each site shown in the location maps given in Appendix 4.1. This appendix also provides details of each site, including the grid reference and results from the analysis of soil samples. The erosion monitoring and its results are described below for each site in turn.

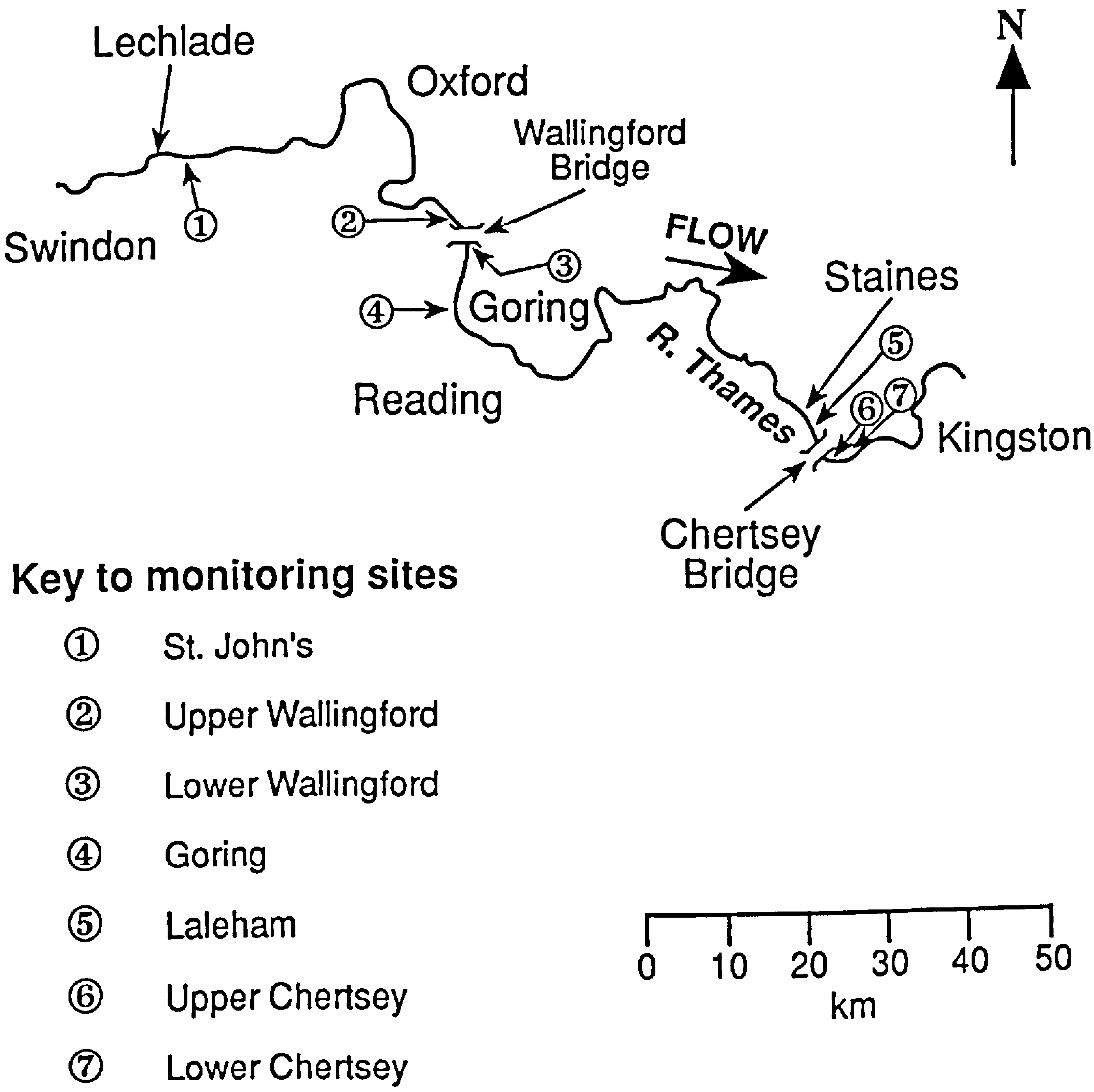


Figure 4.1 Location of the seven bank erosion monitoring sites on the River Thames.

4.2 St.John's

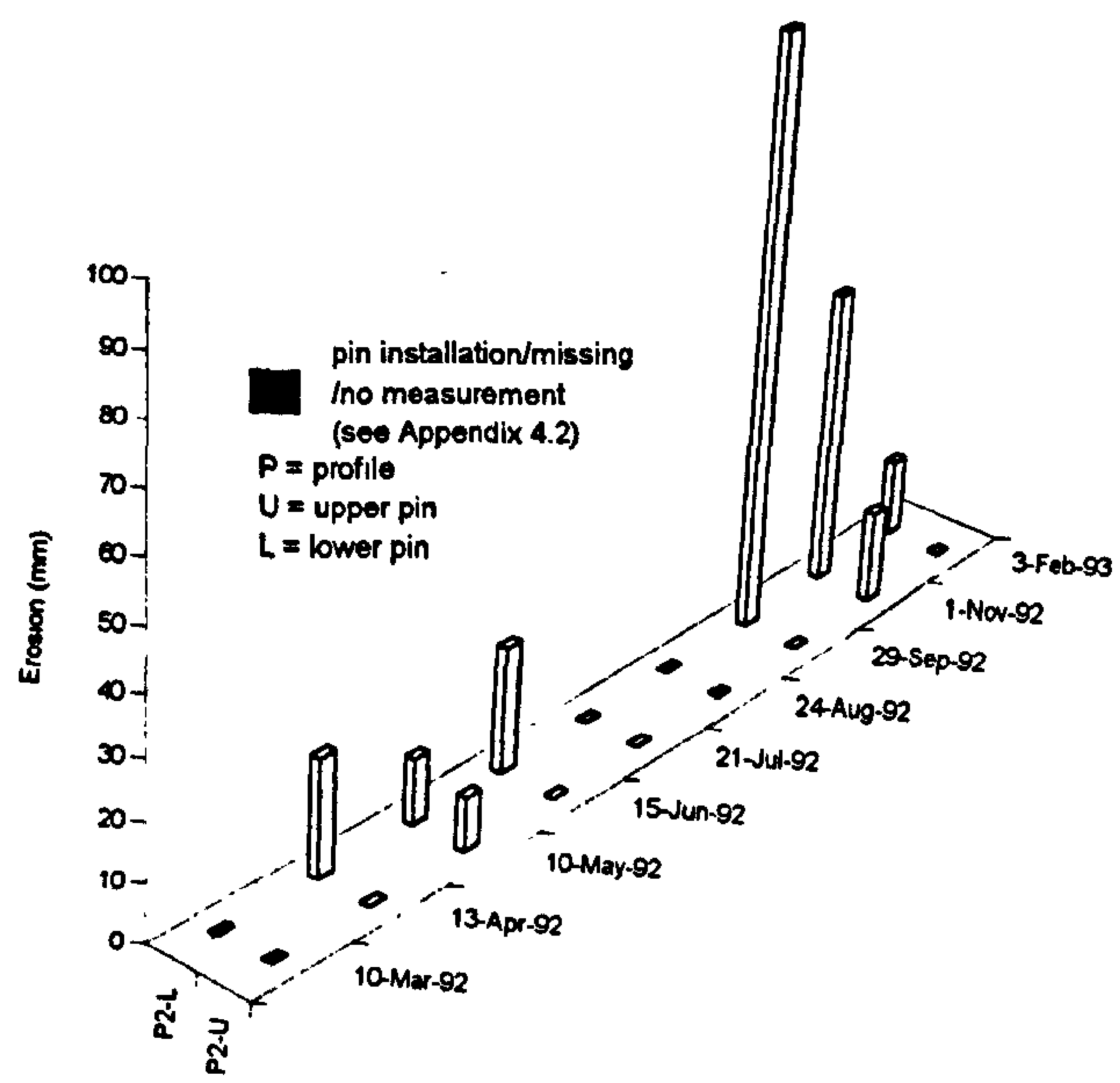
The St. John's monitoring site is located on the right bank downstream of St.John's Lock, along the upper reaches of the River Thames, as shown in Appendix 4.1. Monitoring of erosion at St. John's commenced on 10 March 1992, when five bank profiles were surveyed along a 20m bank line, and an erosion pin installed at the upper and lower bank at profile two. A site plan showing the positions of the bank profiles and the location of the erosion pins is given in Appendix 4.1. The site was resurveyed, prior to the peak boating season, on 6 July 1992 and again, after the boating season, on 1 November 1992 and a final survey was carried out on 3 February 1993.

Plate 4.1 is an upstream view of the monitoring site showing the low, poorly vegetated bank and the extent of the winter reed bed. Cattle grazed the adjacent field for most of the summer and accessed the water at the survey site. The reed bed flourished during the summer and, to some extent, so did the vegetation on the bank.

Plate 4.1 Upstream view of St. John's monitoring site.

Details of this site, including analysis of soil samples, are given in Appendix 4.1 and shear strength and soil suction measurements taken during the monitoring period are shown in Appendix 4.3. The length of erosion measured at each pin installed in the bank at profile two was recorded during each visit to the site and is shown in Figure 4.2, and listed in Appendix 4.2. It should be noted that neither of the erosion pins could be relocated on 24 August 1992 and two replacement pins were installed in the bank (see later). The corresponding bank profile surveyed (profile two) is shown in Appendix 4.4, along with the surveys of the other four profiles.

Figure 4.2
Erosion measured at the St. John's monitoring site.



The survey of the bank at profile one shows the inconsistencies between the surveys at distances greater than about 3.5m from the baseline. This distance marks the edge of the upper bank. At distances greater than about 3.5m, the bank was unvegetated in winter and vegetated with grass and some reeds encroaching from the channel during summer. These seasonal changes in vegetation cover, in addition to cattle trampling, were probably responsible for the changes in the lower bank.

During the first survey, in March 1992, the reeds in front of the bank were sparse and flattened. Vegetation, particularly the reeds, increased during summer and the reduced flow velocities within the reed bed may have encouraged sediment deposition. The third survey was taken after the high flows in September 1992 and shows the change in the profile since the previous July. The last survey of the bank, at the beginning of February 1993, shows retreat of the bank and some erosion of the lower bank material.

Although erosion mechanisms are impossible to isolate completely, contributory factors include cattle trampling, which results in mechanical damage to the bank, boat wash and the high flow velocities experienced in the autumn and winter. During the winter months, boat traffic is at a minimum and the banks were no longer grazed by cattle. However, the protective reeds and bank vegetation died back, leaving the bank more exposed to the erosive force of the high winter discharges.

Limited upper bank erosion was measured during the first two months of the monitoring period (10 March to 10 May 1992), when there was 9mm of erosion, compared to 31mm at the lower bank. Disregarding the August result, when the upper and lower banks were repinned, the only other erosion of the upper bank took place between 29 September and 1 November 1992, when 15mm of erosion was recorded. From the seasonal pattern of upper and lower bank erosion, the high autumn flows appear to have made a considerable contribution to erosion. However, without the erosion pin exposure data for August 1992, the contribution to erosion during the summer is unknown.

The bank surveys taken at profile two indicate that there was approximately 300mm of erosion at the lower bank between 6 July and 1 November 1992. There must therefore, have been approximately 150mm of lower bank erosion between 21 July and 24 August 1992. The surveys also shows far less upper bank erosion over this time, no more than about 100mm, so that there was approximately 85mm of erosion at the upper bank between 21 July and 24 August 1992. The bank surveys at profiles three, four and five show varying degrees of upper and lower bank distortion. These changes in the bank can be attributed to cattle trampling and changes in bank vegetation and reed growth, all of which had a significant influence on the bank morphology.

Erosion at the upper and lower bank of profile two was least during the spring, from 10 March to 10 May 1992, and greatest during the summer, from 10 May 1992 to 24 August 1992. The summer period corresponds to the peak boating season, and during the months of May, June and July 79% (4901 vessels) of the total traffic in 1992 passed through St.John's Lock, upstream of the monitoring site (see traffic through Buscot Lock listed in Appendix 4.6). This period also includes the grazing season, and evidence of damage to the bank from cattle trampling was extensive. In fact the inability to relocate the erosion pins during the August visit could be attributed to distortion of the bank from cattle accessing the water's edge.

The monitoring site is located along the outer bank of a bend. The low banks were relatively saturated in all but the driest conditions when desiccation caused cracking of the soil surface where vegetation was sparse. With the increase in discharge during the autumn and winter, the banks became saturated and the deterioration in soil structure during summer desiccation, together with cattle trampling, led to the reduction in soil strength observed during wet conditions. Appendix 4.3 shows the shear strength and soil suction measured at intervals during the monitoring period.

The lower bank erosion during the winter period was comparable to that during the summer, whereas upper bank erosion was lower in winter. The dominant erosive force during the winter period was the river discharge which peaked at approximately $60m^3/s$ on 30 November 1992. To illustrate the magnitude of the winter flow compared to the normal flows experienced here, a discharge hydrograph, from flow recorded at a gauging station (Buscot) downstream of the monitoring site, is shown in Appendix 4.5.

Between 24 August and 29 September there was 100mm of erosion at the lower bank, whereas there was no erosion of the upper bank whatsoever. With an erosion pattern such as this occurring at this time of year, when grazing had ceased and boat traffic for the month was only 11% of the annual total (701 vessels), it would suggest that erosion was primarily a result of the relatively high autumn discharges. The discharge hydrograph in Appendix 4.5 shows a low peak in flow towards the end of August and the second peak in mid

September, prior to the site visit on 29 September 1992.

Comparing the erosion measured at the pins in profile two on the last three visits, total erosion at the upper pin was 15mm from 24 August to 1 November 1992, and zero from 1 November 1992 to 3 February 1993. At the lower bank, erosion was 150mm and 13mm for these durations, respectively. The maximum daily discharges during these respective periods were 15.3m^3/s and 58.5m^3/s, although more erosion took place during the lower flow. It was not until 11 November that discharges again exceeded the 15.3m^3/s on 26 September.

From the magnitude of erosion and its timing, conclusions can be drawn regarding the processes that dominated erosion through the monitoring period. Erosion during the spring period was low, and may well have been due to some degree of cattle trampling, perhaps in combination with a high flow in early April, when the discharge peaked at 15.6m^3/s (higher than the September peak discharge).

The primary determinant of erosion during the summer period was cattle trampling the banks causing mechanical damage and reducing the soil strength. Summer erosion may be exacerbated by high spring discharges or boat wash removing loose material from the bank, however, traffic here is not excessive and the sinuosity of the channel means that craft may often slow down when travelling round the bend. In addition, bend geometry means that the outer bank receives lower concentrations of wave energy from boat wash than straight channels, so the contribution to summer erosion from boat wash is probably relatively minor.

During the winter there were two erosion events to be considered: erosion during the September flows and, then again, during the November and December flows. Although the November flows were far higher, more erosion was observed to result from the lower flows in September. There appears to be an additional factor influencing the September erosion to account for this.

This may be attributed to cattle trampling the banks and loosening bank material which could then be washed away by the flow in September.

Preparatory factors such as cattle trampling played no part in the erosion mechanism after the September flows, and so erosion measured on the 3 February 1993 would include erosion from the 1 November 1992 due only to the high discharges and factors such as wetting and drying cycles and freezing and thawing. The only erosion measured at profile two during this period was 13mm at the lower bank. This would indicate that during the winter, although the channel discharge may have been sufficient to remove weakened bank material, as it did during the lower September flows, there may have been insufficient vulnerable (i.e. weakened) bank material available that had not already been removed by the September flows.

To summarise the determinants of erosion at this site the erosion mechanisms must be assessed in a temporal context and relative to one another. Erosion from cattle trampling is probably the dominant mechanism during the summer, and is also a vital mechanism for increasing the bank's susceptibility to erosion from high flows. High discharges towards the end of 1992 were responsible for the winter erosion. However, without the summer cattle damage to weaken the bank, their contribution to erosion may not have been quite so significant.

Section 4.9 reviews the processes and mechanisms of erosion at St. John's in relation to the other monitoring sites.

4.3 Upper Wallingford

The location of the Upper Wallingford monitoring site, on the right bank upstream of Wallingford Bridge, is shown in Appendix 4.1 together with a site plan showing the positions of the bank profiles and erosion pins. The four most upstream bank profiles were initially surveyed on 24 January 1992, and the two most downstream profiles on 5 February 1992. Erosion pins were installed in the upper and lower bank at each of the three most downstream profiles (profiles four, five and six). The site was resurveyed on 6 July 1992, 30 October 1992 and finally on 2 February 1993. A record of the survey dates and results from soil sample analysis as well as other site details are given in Appendix 4.1. Peak and residual shear strength, and soil suction measurements taken during the monitoring period are shown in Appendix 4.3.

Plate 4.2 is an upstream view, taken from the left bank, of the upstream half of the monitoring site. The steep, unvegetated bank face marks the position of profile four, and profiles one, two and three are upstream of this. The downstream half of the monitoring site is shown in Plate 4.3, where the red buoy in this photograph marks the position of profile five, and profile six is just upstream of the moored boat.

Plate 4.2 Upstream view of the Upper Wallingford monitoring site (upstream profiles).

Plate 4.3 Downstream view of the Upper Wallingford monitoring site (downstream profiles).

The erosion measured at the upper and lower banks at profiles four, five and six is shown in Figure 4.3, and listed in Appendix 4.2. Surveys of the bank taken at profiles one to six are shown in Appendix 4.4.

At profile one, the bank was well vegetated with reeds at the toe. The change between the first and second surveys was minimal, and possibly due to seasonal changes in the reed bed. During the first survey, temperatures were low and frozen water round the reed bed allowed the survey to extend into the channel. The high flows during autumn and winter made surveying at comparable distances during the last two surveys more difficult. The last survey suggests some erosion occurred between 30 October 1992 and 2 February 1993. However, this was not so much bank retreat, as a lowering of the lower bank, presumably as a result of the high winter flow in combination with changes in vegetation.

The bank was also well vegetated at profile two, particularly during the summer, which was reflected in the survey taken in July 1992, where the vegetation raised the apparent height of the lower bank. Flattening of the bank vegetation during the high autumn flows meant that the apparent height was raised further for the October survey. Not until after the high winter flows, at the end of 1992, was the height again lowered, when the vegetation had sufficiently died back.

The surveys taken of the bank at profile three show that the majority of upper bank erosion occurred between the first two survey dates. Changes in vegetation, particularly at the lower bank, were also reflected between these surveys. The surveys also show erosion of the lower bank during the winter, from the end of October 1992 to the beginning of February 1993, which coincides with the timing of the peak flow through the reach.

Erosion pins were installed at the upper and lower bank of profile four, and Figure 4.3 shows the amount of erosion measured at each pin during the monitoring period. These amounts are also listed in Appendix 4.2. The bank at this profile is steep, high and unvegetated throughout the year, and the bank surveys in Appendix 4.4 show a gradual retreat of the upper and lower bank at each survey.

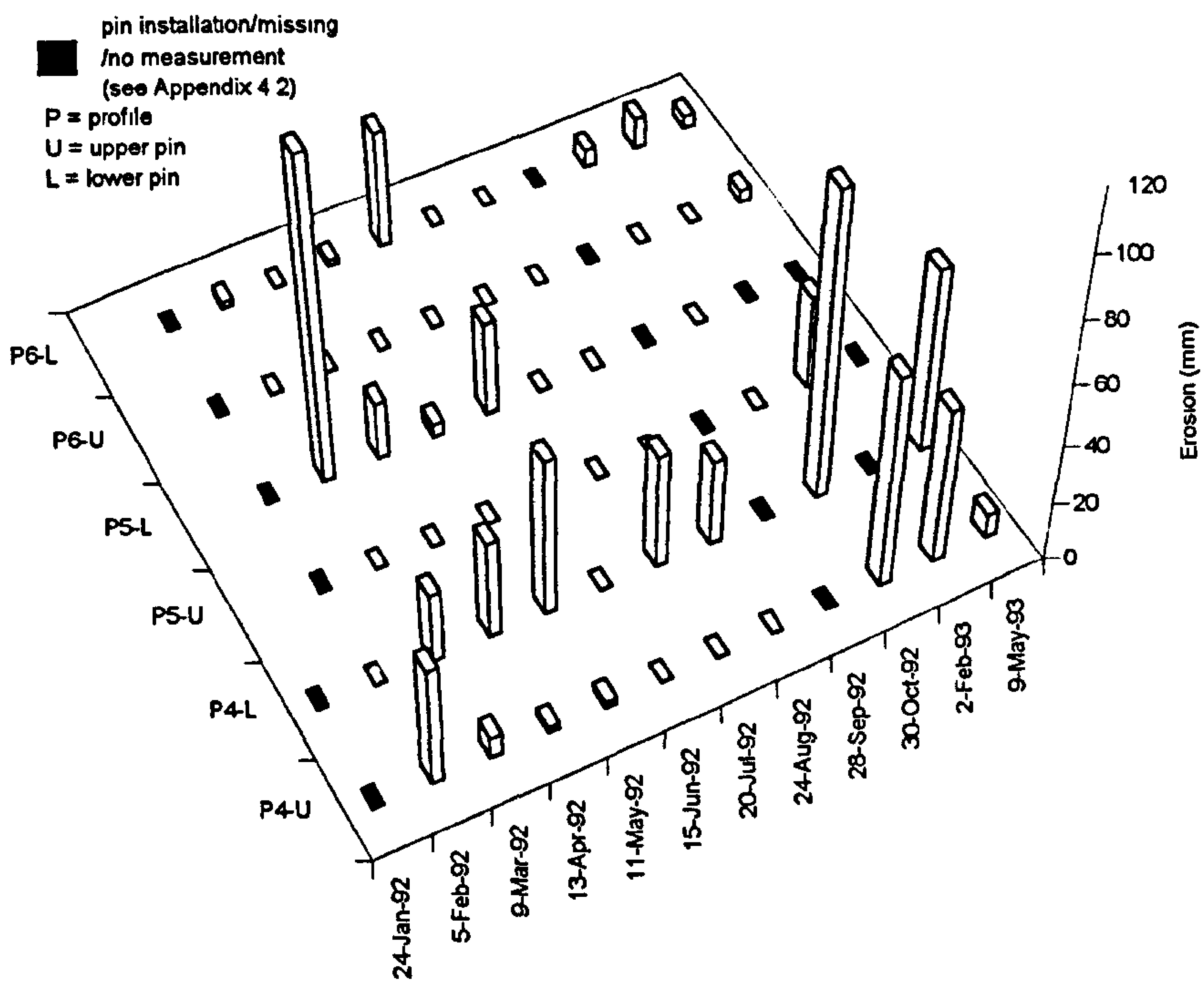


Figure 4.3 Erosion measured at the Upper Wallingford monitoring site.

The pattern of erosion shown in Figure 4.3 indicates that, at profile four, upper bank erosion was dominant at the beginning of 1992, with no erosion of the lower bank until after the visit in February 1992. From the March 1992 visit onwards, lower bank erosion was dominant, and no upper bank erosion what so ever was measured between 11 May and 24 August 1992. The visit in October 1992 was after the high autumn flows, when 71mm and 100mm of erosion were measured at the upper and lower bank, respectively. The next visit to the site, in February 1993, was after the winter floods. By this time the upper bank had eroded by a further 52mm and deposition had occurred at the lower pin. A final site visit on 9 May 1993 showed that since February 1993 the upper and lower banks had eroded by 8mm and 60mm respectively. This corresponded to a time when there was a further peak in discharge (see discharge hydrograph at Sutton Courteney, Appendix 4.5).

The bank surveys at profile five are also shown in Appendix 4.4. The erosion measured at each of the pins at this profile is given in Appendix 4.2 and also shown in Figure 4.3. Anglers accessed the water's edge from here and some broken concrete bagwork at the toe of the bank allowed them to stand in the channel during the low summer flows. The erosion pins installed at this profile were thus placed about one metre downstream from the actual bank profile surveyed to avoid potential danger to anglers using the bank. The erosion pin site was higher, steeper and less vegetated than the profile surveyed which, although high, was shelved and more densely vegetated.

Figure 4.3 shows that the only erosion measured at the upper bank of profile five was between 30 October 1992 and 2 February 1993 and amounted to 30mm. Erosion of the lower bank was highest at the beginning of the monitoring period, from 5 February to 9 March 1992 and, to a lesser extent, continued up to 15 June 1992. No erosion was measured throughout the rest of the monitoring period and in February 1993 material was deposited over the pin.

The surveys of the bank at profile five show more erosion than was measured at the pins. The change in profile due to the summer vegetation is clearly shown between the first two survey dates. So too is the change in profile after the high autumn flows during which there was erosion of the upper bank and shelf. The last bank survey, taken after the winter flood flows, shows even more erosion at both the upper bank and lower bank, and deposition at the toe of the bank.

The surveys of the bank at profile six, shown in Appendix 4.4, and the erosion at the upper and lower pins, shown in Figure 4.3, show that there was little erosion at this profile throughout the monitoring period. Most erosion was measured at the lower pin between 11 May and 15 June 1992 and may be attributed to a boat mooring here from spring time until the high autumn flows. Some erosion of the lower bank was also measured after the autumn flows and again after the winter floods, 6mm and 10mm, respectively, however, there was no upper bank erosion during these periods. Both the upper and lower banks then eroded by a further 4mm between 2 February and 9 May 1993. The total erosion measured at the upper and lower banks throughout the monitoring period amounted to only 4mm and 63mm, respectively.

During spring, at the beginning of the monitoring period, the banks will have suffered from some degree of frost attack since temperatures were low and vegetation sparse, leaving the bank material exposed to the freezing and thawing conditions which cause loosening of the soil particles. This freezing and thawing was particularly evident at profiles four and five where the banks were high and steep, and the face of the bank unvegetated during the winter. There was erosion at both the upper and lower bank of profile four during spring, and the most erosion at the lower bank at profile five was also during spring. Only 4mm total erosion was measured at the upper bank of profile six, and this was after the winter floods. The mooring of the boat here contributed substantially to the total erosion at the lower bank, furthermore, the increased vegetation at profile six may have protected the bank from wetting and drying cycles and frost action.

The influence of the high autumn and winter flows is particularly apparent at profile four. Plate 4.4 is an upstream view of the left bank upstream of Wallingford Bridge, taken during the high autumn flows on 28 September 1992. Plate 4.5 shows the same stretch of river taken during the winter floods on 30 November 1992 when the water level was well above bankfull discharge, inundating the flood plain. For comparison, Plate 4.6 shows the flow in May 1993 when winter discharges had subsided.

Plate 4.4
Upper Wallingford during the high autumn flows in September 1992.

Plate 4.5
Upper Wallingford during the high winter flows in November 1992.

Plate 4.6
Upper Wallingford after subsidence of the high flows (May 1993).

An estimate of the bankfull discharge at this site is 160m^3/s (Thames Water 1988b). With the data available from flow gauging stations at Sutton Courtenay (upstream of Wallingford) and Reading (downstream of Wallingford), the peak discharges at Wallingford during the high autumn flows and the winter floods can be estimated at approximately 100m^3/s near to 27 September, and 186m^3/s near to 5 December, respectively. The discharge hydrographs for all the available discharge data from the Sutton Courtenay (upstream) and Reading (downstream) flow gauging stations are given in Appendix 4.5.

The autumn flows eroded the upper bank at profile four, and the lower bank more so. The winter flow however, only eroded the upper bank, and to a lesser extent than the erosion during the autumn period. This could imply that prior to the erosion during the autumn, the material on the face of the bank may have been made more susceptible to erosion and was then easily removed by the autumn bankfull discharges. When the winter flood came to erode the bank, there was less weakened material available to be removed by the over bankfull flows. Factors that encourage weakening of the bank material may be responsible for increasing the amount of material available for erosion during the autumn, as opposed to during the winter. These factors at profile four include the lack of vegetation, pedestrian traffic on the adjacent footpath, desiccation and boat wash. Deposition observed at the toe of the bank after the subsidence of high flows also suggests that some failure of bank material occurred as a result of the drawdown of flow and its associated changes in pore water pressure within the bank material.

Section 4.9 reviews the processes and mechanisms of erosion at Upper Wallingford in relation to the other monitoring sites.

4.4 Lower Wallingford

The location of the Lower Wallingford monitoring site, on the left bank downstream of Wallingford Bridge, is shown in Appendix 4.1, along with a site plan showing the positions of the bank profiles and erosion pins. The site, with eight profiles, was initially surveyed on 3 January 1992 when erosion pins were placed in the upper and lower bank at each profile. A second survey was carried out 16 June 1992 at the four upstream profiles and 6 July 1992 at the four downstream profiles. All eight profiles were surveyed for a third time on 30 October 1992 and finally on 2 February 1993.

As with the other monitoring sites, a record of the survey dates and results from soil sample analysis as well as other site details are given in Appendix 4.1. The erosion measured at each of the pins installed at the site is given in Appendix 4.2, where peak and residual shear strength and soil suction measurements taken during the monitoring period are shown in Appendix 4.3.

Plate 4.7 is a downstream view of the Lower Wallingford monitoring site, taken from Wallingford Bridge. The bank here is high and steep. The face of the bank remained unvegetated for most of the year, with summer vegetation being restricted only to the few parts where the bank is sufficiently shelved to facilitate colonisation.

Plate 4.7 Downstream view of the Lower Wallingford monitoring site.

The amount of erosion measured at each pin during the site visits is given in Appendix 4.2 and shown in Figure 4.4. As with the other monitoring sites, bank surveys taken at each profile are shown in Appendix 4.4.

Figure 4.4, along with the bank survey, show the total erosion at the upper bank of profile one through the monitoring period to be comparable to that at the lower bank. However, the majority of the lower bank erosion was during the summer, from 20 July to 24 August 1992, when 81mm of erosion was measured, compared to the majority of the upper bank erosion being during the high autumn and winter flows. After the autumn flows 40mm of upper bank erosion was measured, compared to 48mm on 2 February, after the winter floods.

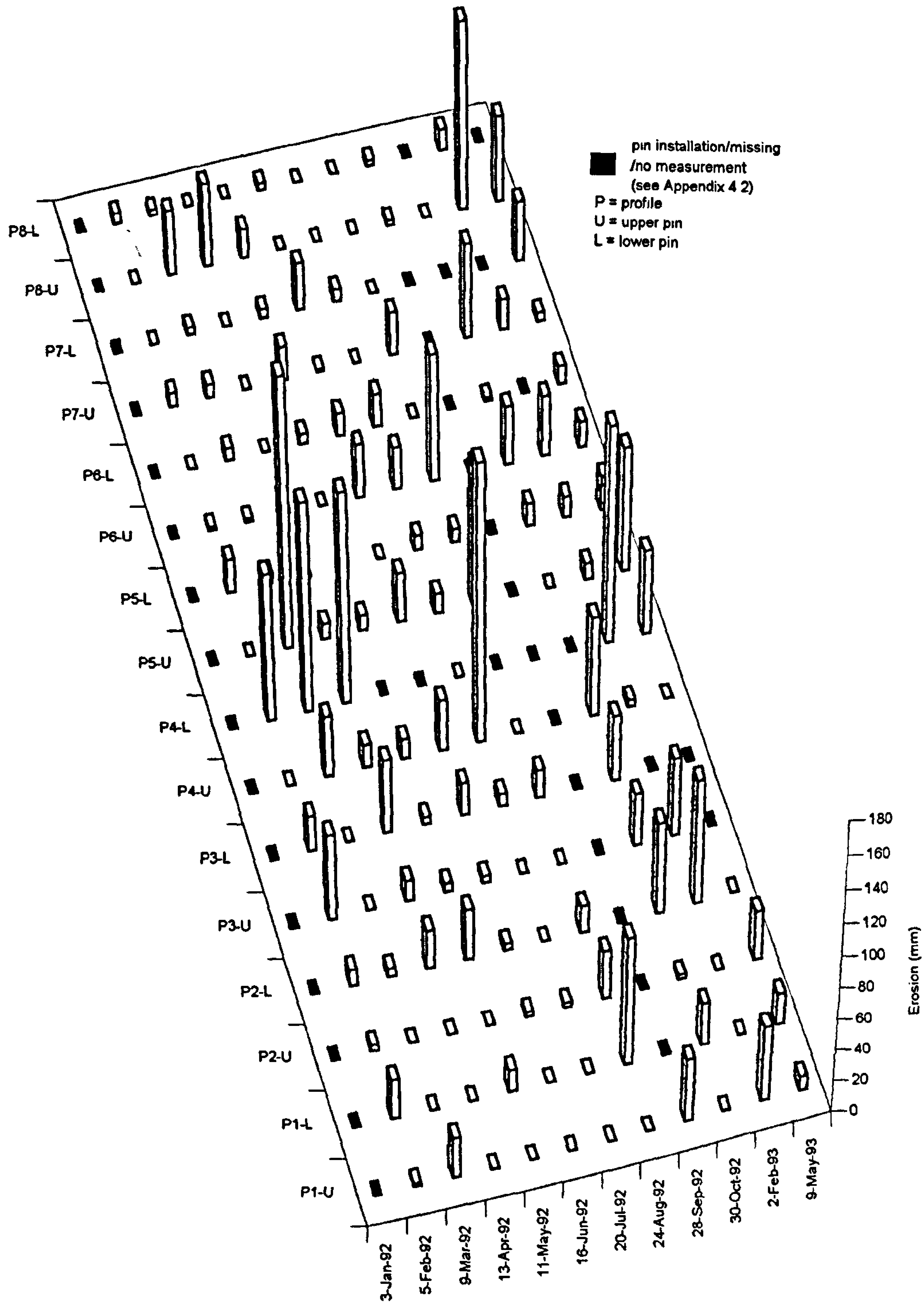


Figure 4.4 Bank erosion measured at Lower Wallingford.

Plates 4.8 and 4.9 were taken at this site during the high autumn and winter flows, respectively. These were taken from Wallingford Bridge and show a downstream view of the monitoring site. Profile one is just downstream of the small unvegetated gully visible in Plate 4.8 but inundated in Plate 4.9. Lower bank erosion at profile one was also substantial in spring 1992 and spring 1993 which may be as a result of frost action and cycles of wetting and drying. Plate 4.10 was taken on 24 January 1992, just downstream of profile one, and shows the freezing conditions at the lower bank.

Plate 4.8 Lower Wallingford during the high autumn flows in September 1992.

Plate 4.9 Lower Wallingford during the high winter flows in November 1992.

Plate 4.10 Freezing conditions at the Lower Wallingford monitoring site.

The surveys taken at profile two are also shown in Appendix 4.4. Figure 4.4 shows that the majority of lower bank erosion was measured after the high flows in autumn and winter, 55mm and 75mm, respectively, whereas the most upper bank erosion measured at one visit was 30mm for both the periods between 16 June and 24 August 1992 and 2 February to 9 May 1993.

At profile three the most upper bank erosion measured was 51mm between 3 January and 5 February 1992 however, the cumulative contribution to upper bank erosion from the autumn and winter discharges amounted to 80mm. The lower bank erosion measured between 9 March and 13 April 1992 amounted to 45mm and was the most recorded at the lower bank in any one visit. However, after the autumn flows an additional 40mm of erosion was recorded here, and the pins could not be relocated again during the monitoring period. Bank failure had not occurred to any great extent at profile three prior to the February 1993 survey as the bank survey shown in Appendix 4.4 would have collaborated with this. In addition, the upper erosion pin was located on the February visit but the high flow prohibited measurement of erosion at the lower pin. The appearance of the bank would suggest that there had not been any significant retreat of the bank since the visit to the site in February 1993. However, the toe of the bank had obviously been undercut in the vicinity of the lower pin and the upper pin had been deliberately dug out of the bank (see Plate 4.11).

Plate 4.11 Undercutting at the toe of the bank at profile three.

Figure 4.4 takes no account of the inability to relocate the lower erosion pin at profile four on several visits to the site (see Appendix 4.2). New erosion pins were installed in the lower bank on each occasion but erosion was recorded as zero in Figure 4.4. There will thus have been a great deal more erosion of the lower bank than this figure implies, which is reflected in the surveys of the bank profile shown in Appendix 4.4. From the erosion actually measured, there would appear to have been the greatest amount of lower bank erosion between 13 April and 11 May 1992, there was probably substantially more than 128mm of lower bank erosion during the summer when undercutting was evident, and also after the high autumn flows. This is confirmed by the bank surveys

Upper bank erosion at profile four was undoubtedly highest between 16 June and 20 July 1992, when 168mm was measured. The next highest contribution to erosion of the upper bank was after the high autumn discharges, when 60mm was recorded. The bank surveys show the upper bank and lower bank retreat between the first two surveys, and the retreat of the lower bank shelf after 16 June 1992. Undercutting of the bank was observed immediately below the lower erosion pin which resulted in the pin itself being undercut several times as the toe of the bank retreated (see Plate 4.12).

Plate 4.12 Undercutting at the toe of the bank at profile four.

Figure 4.4 shows the most upper bank erosion measured at profile five was 161mm, between 5 February and 9 March 1992, which was 41% of the total upper bank erosion during the whole monitoring period. A further 37% of the total upper bank erosion was measured between 9 March and 24 August 1992, while less than 3% of the total was measured between 24 August 1992 and 2 February 1993. Upper bank erosion at profile five was considerably higher than lower bank erosion, and the bank surveys in Appendix 4.4 reflect this. The total amount of erosion measured at the upper and lower bank during the whole of the monitoring period were 391mm and 90mm, respectively. The most lower bank erosion measured at any one visit was 20mm, for both the periods from 3 January to 5 February 1992 and 2 February to 9 May 1993. Together these constitute 44% of the total lower bank erosion during the entire monitoring period, and lower bank erosion after the autumn and winter flows, that is from 24 August 1992 to 2 February 1993, constituted 30 % (27mm) to the total.

At profile six, the total erosion measured during the monitoring period was substantially higher for the upper bank than the lower bank. This is shown in Figure 4.4 and the bank surveys in Appendix 4.4. The most upper bank erosion measured at one time was for the period between 20 July and 24 August 1992, which amounted to 74mm, 33% of the total throughout the monitoring period. The most lower bank erosion was between 16 June and 24 August 1992 and, although only 19mm, this also amounted to 33% of the total lower bank erosion. Between the 11 May and 24 August 1992 erosion of the upper and lower banks amounted to 59% and 56% of the respective totals recorded over the whole monitoring period. In comparison, between 24 August 1992 and 2 February 1993 erosion of the upper and lower banks amounted to 31% and 21% of the total, respectively.

Again, at profile seven, total upper bank erosion was higher than at the lower bank, 140mm and 79mm, respectively. The most upper bank erosion, 56mm, was measured after the high autumn flows on 30 October and amounted to 40% of the total for the whole monitoring period. A further 13% was measured after the winter floods bringing the contribution to the total upper bank erosion, from the high discharges, to 53%. This compares with 32% of the total upper bank erosion measured for the period between 13 April and 24 August 1992. For this same period lower bank erosion constituted 51% to the total, whereas this was 44% from 24 August 1992 through to 9 May 1993.

Total erosion measured at the upper and lower banks of profile eight amounted to 267mm and 28mm, respectively, through the monitoring period. The most upper bank erosion was measured after the winter flood flows, on 2 February 1993, when 110mm, 41% of the total, had eroded since 30 October 1992. Appreciable upper bank erosion, 33% of the total, was also recorded between 5 February and 13 April 1992. The small amount of erosion that was measured at the lower bank, was primarily after the winter floods and, although the lower erosion pin could not be relocated on the October visit, the bank surveys and a recollection of the bank profile prior to the autumn flows suggested no significant erosion had taken place and it is presumed that the pin had probably been removed deliberately.

The contribution to erosion during the summer will be primarily from boat wash undercutting and eroding the lower bank, along with recreational access (see Plate 4.13) and the influence of wetting and drying cycles. Desiccation of the upper bank led to crumbling of the root zone, while drying of the lower bank led to shrinkage and cracking of clay toe (Plate 4.14).

Plate 4.13 Recreational access at Lower Wallingford.

Plate 4.14 Erosion of the clay toe at Lower Wallingford.

The pattern of erosion at this site also demonstrates the importance of the high autumn and winter flows in eroding the bank material, as well the influence of the factors which contribute to weakening of the bank material. High discharges (at and above bankfull) made a significant contribution to bank erosion through entrainment of weakened particles on the surface of the bank material. Plate 4.15, taken after the peak winter floods, shows the smoothed surface of the bank material. Subsidence of high flows also resulted in failure and Plate 4.16, taken after subsidence of the high autumn flows, clearly shows failed material at the base of the bank.

Section 4.9 reviews the processes and mechanisms of erosion at Lower Wallingford in relation to the other monitoring sites.

Plate 4.15 Smoothed surface of bank material following peak flood flows.

Plate 4.16 Bank failure following subsidence of high flows in autumn 1992.

4.5 Goring

The location of the Goring monitoring site, on the right bank upstream of Goring Lock, is shown in Appendix 4.1 along with a site plan showing the positions of the bank profiles surveyed. The bank here is protected with Nicospan which is failing in some places along the length of the reach. An upstream view of the profile site on the right bank is shown in Plate 4.17.

Plate 4.17 Upstream view of the Goring monitoring site.

Two erosion pins were installed in the upper and lower bank, downstream of the profile site, and a downstream view of the erosion pin site, upstream of Goring Lock, is shown in Plate 4.18. Plate 4.19 is the same site photographed on 30 November 1992 when the flow was over the top of the bank.

Plate 4.18 Location of erosion pins at the Goring monitoring site.

Plate 4.19 High flows at Goring in November 1992.

Details of the Goring site, including analysis of soil samples, are given in Appendix 4.1 and shear stress and soil suction measurements taken during the monitoring period are shown in Appendix 4.3. The erosion measured at the upper and lower pin during each site visit is given in Appendix 4.2 and shown in Figure 4.5.

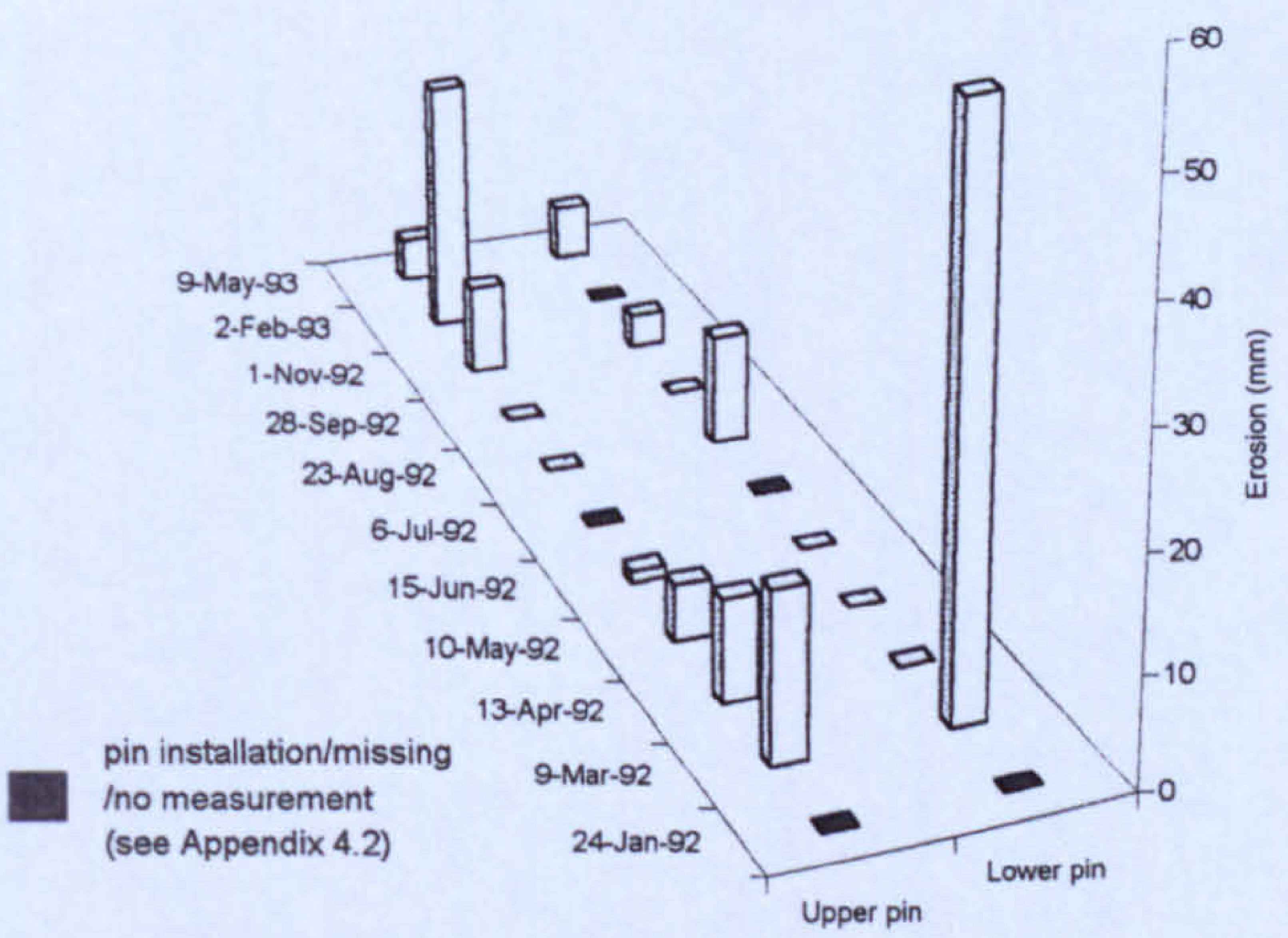


Figure 4.5 Bank erosion measured at Goring.

The amounts of upper and lower bank erosion measured through the monitoring period were comparable, 65mm and 70mm, respectively. The highest upper bank erosion measured during any one visit was 23mm, measured after the high winter floods, compared to maximum of 52mm measured at the lower bank for the period between 24 January and 9 March 1992. Combining the total erosion measured after both the high discharges, the upper bank erosion amounted to 31mm, 48% of the total for the whole monitoring period. Lower bank erosion during this same period amounted to 8mm, almost 12% of the monitoring period total.

It should be noted that neither of the erosion pins could be relocated on the July visit. Localised distortion and shearing of the bank suggested that mooring had flattened the face of the bank, not to such an extent as to erode the pins, but sufficient to make it impossible to relocate them. Two replacement erosion pins were installed and the contribution to erosion on the July visit to the site was recorded as zero.

The bank here is low (<0.5m), and remained saturated most of the year, with frost action during the early part of the monitoring season probably responsible for the majority if the spring time erosion. Frost action was particularly significant at the lower erosion pin, which was placed at the level of the water surface (Plate 4.20).

Plate 4.20 Frost action at Goring.

During the course of the monitoring period there were signs of grazing on the land adjacent to the bank, but the site was certainly not over grazed, and there were no specific cattle access points or characteristic indicators of cattle trampling. The summer erosion was thus restricted primarily to the mechanical damage from mooring mentioned above. The erosion during the flood period may have been more significant had the site been situated differently relative to the main channel flow. The site is positioned where the channel widens to divide between the entrance to Goring lock and the weir stream (see location map in Appendix 4.1). At the point where the channel widens, flow velocities, particularly at the periphery, will be reduced, although this length of bank is on the approach to the weir stream.

No significant change in the integrity of the Nicospan was observed throughout the monitoring and this is reflected in the surveys shown in Appendix 4.4, although there is some indication of small changes in the sediment at the toe of the Nicospan.

Section 4.9 reviews the processes and mechanisms of erosion at Goring in relation to the other monitoring sites.

4.6 Laleham

The location of this monitoring site, on the left bank at Laleham, is shown in Appendix 4.1, together with a site plan showing the positions of the erosion pins. Details of this site, including analysis of soil samples, are given in Appendix 4.1 and shear stress and soil suction measurements taken during the monitoring period are shown in Appendix 4.3.

Plate 4.21 is a downstream view of the location of the erosion pins on the left bank, where the erosion pin installed in the lower bank can be seen painted red in the recess just upstream of the failed bagwork. Laleham is extremely popular for angling and recreation in general, particularly during the summer, and camping, parking and other recreational facilities are provided nearby.

Plate 4.21 Downstream view of the Laleham monitoring site.

The erosion measured at the upper and lower pins at each visit to the site is given in Appendix 4.2 and shown in Figure 4.6. Neither pin could be relocated on the visit in May 1993 and the appearance of the bank suggested that approximately 0.5m of bank erosion had occurred. Plate 4.22 is a downstream view of the bank taken on 9 May 1993 which clearly shows the retreat of the bank behind the bagwork and enlargement of the spending beach.

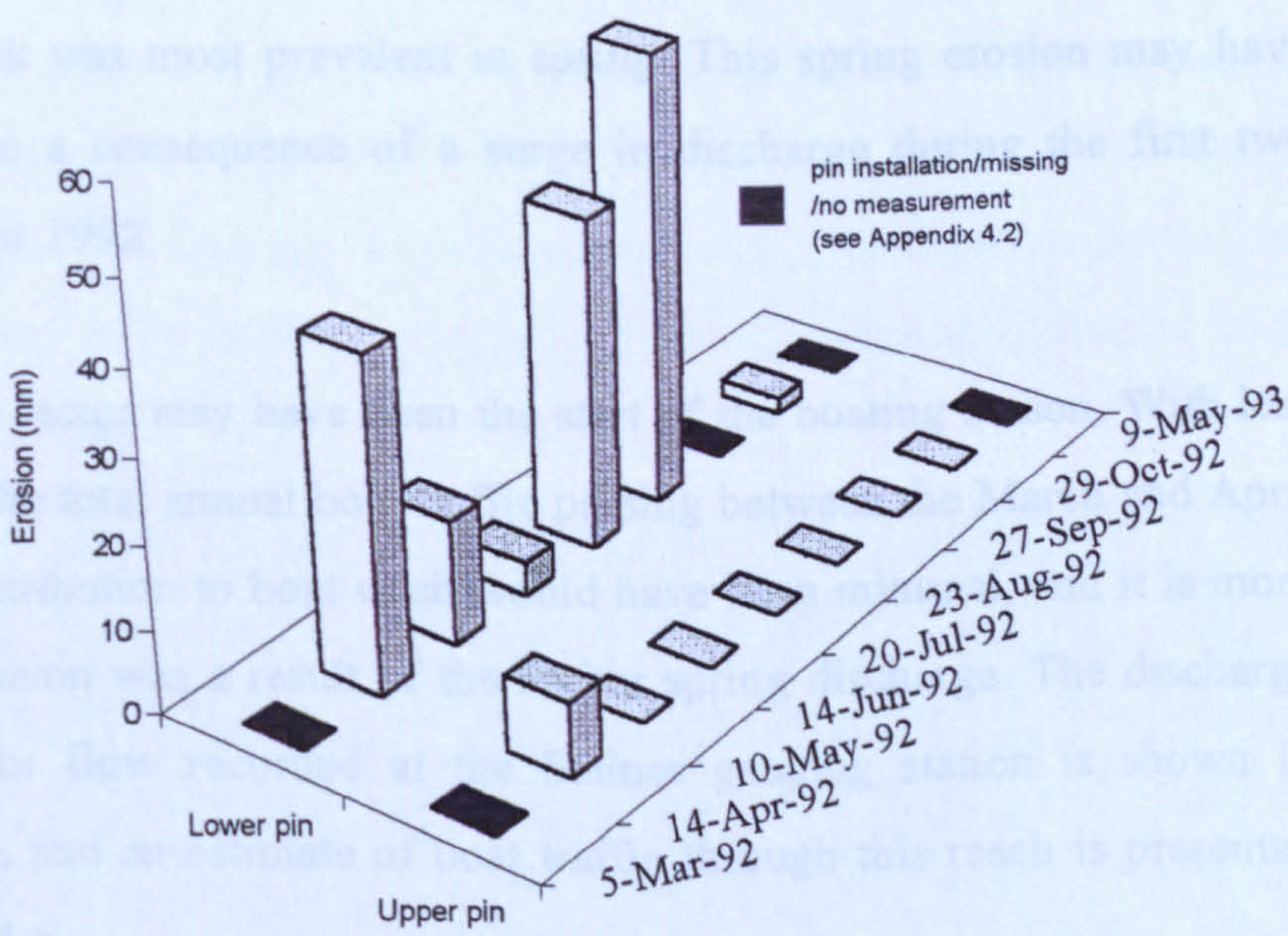


Figure 4.6 Bank erosion measured at Laleham.

Plate 4.22 Downstream view of the Laleham monitoring site following bank retreat.

The total amount of upper and lower bank erosion measured up to 29 October 1992 was 9mm and 155mm, respectively. Besides the influence of the winter flood, the summer period dominated erosion of the lower bank and erosion of the upper bank was most prevalent in spring. This spring erosion may have primarily been a consequence of a surge in discharge during the first two weeks of April 1992.

An additional factor may have been the start of the boating season. With less than 10% of the total annual boat traffic passing between the March and April visits, the contribution to boat wash would have been minimal, and it is more likely that erosion was a result of the higher spring discharge. The discharge hydrograph for flow recorded at the Staines gauging station is shown in Appendix 4.5, and an estimate of boat traffic through this reach is presented in Appendix 4.6.

Vegetation on the upper bank increased during the summer, and the low flow exposed a small spending beach which dissipated wave energy from the summer boat wash. Thus the erosion of the lower bank during summer is most probably attributed to boat wash while the upper bank remained untouched throughout the whole season. The bank is low (<0.3m) and comprises a shallow root zone above the sandy beach. Boat wash at the bank was turbulent behind the failed bagwork and it is more than likely that the root zone was undercut below the root mass at the summer water level and thus considerably weakened the bank prior to the high discharges.

Section 4.9 reviews the processes and mechanisms of erosion at Laleham in relation to the other monitoring sites.

4.7 Upper Chertsey

The location of the Upper Chertsey monitoring site, on the left bank downstream of Chertsey Bridge, is shown in Appendix 4.1, along with a site plan showing the positions of the bank profiles and erosion pins. Details of this site, including analysis of soil samples, are also given in Appendix 4.1, and shear stress and soil suction measurements taken during the monitoring period are shown in Appendix 4.3. Plate 4.23 is a view from the river of the site showing the reed bed fringing the bank downstream of a vegetated beach. An upstream view of the monitoring site, with Chertsey Bridge in the background, is shown in Plate 4.24.

Plate 4.23 The Upper Chertsey monitoring site.

Plate 4.24 Upstream view of the Upper Chertsey monitoring site.

This monitoring site was not established until 8 July 1992 when four bank profiles were surveyed along a length of about 15m and erosion pins were installed in the upper and lower bank at each profile. The erosion measured at each pin during the visits to the site is given in Appendix 4.2 and shown in Figure 4.7. The bank surveys taken at each of the profiles are given in Appendix 4.4.

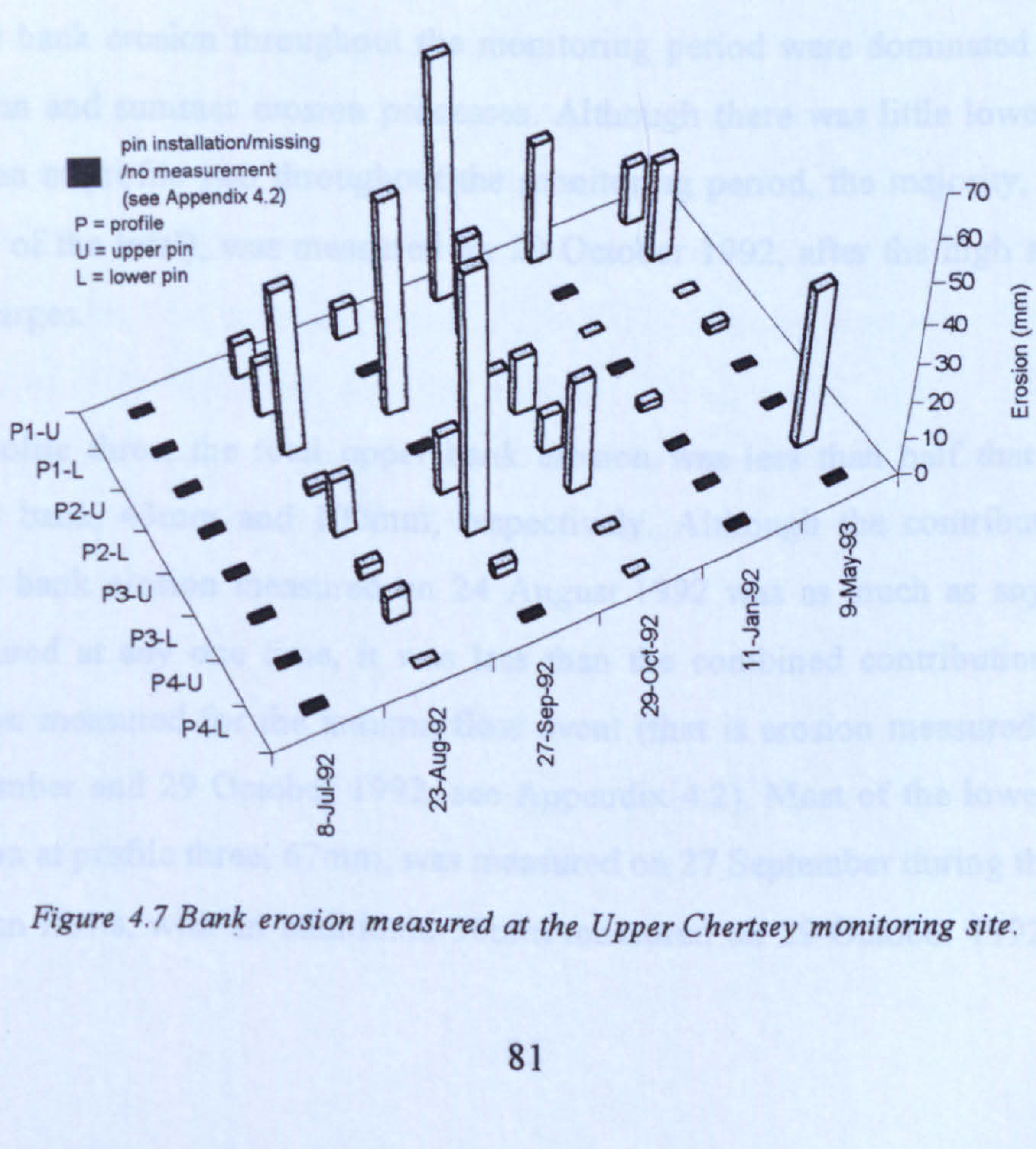


Figure 4.7 Bank erosion measured at the Upper Chertsey monitoring site.

The upper bank erosion measured through the monitoring period at profile one was almost twice that at the lower bank, 122mm compared with 64mm, respectively. Figure 4.7 shows that most upper bank erosion was measured on 29 October 1992, after the high autumn discharges. The most lower bank erosion during any one visit was 25mm, again measured on the 29 October 1992. This would imply that at profile one the high discharges towards the end of 1992 were primarily responsible for the erosion measured at the upper and lower bank.

It should be noted that exposure of the erosion pins installed in the lower bank could not be measured at any of the profiles during the visit on 11 January 1993, since the water level was still to too high after the winter floods.

Again, at profile two, upper bank erosion through the whole monitoring period was greater than at the lower bank, 97mm and 17mm, respectively. The most upper bank erosion measured at any one visit was 54mm, on 27 September 1992, during the high autumn flows. Appreciable upper bank erosion, 43mm, was also measured on 23 August 1992, suggesting that the contributions to upper bank erosion throughout the monitoring period were dominated by the autumn and summer erosion processes. Although there was little lower bank erosion at profile two throughout the monitoring period, the majority, 15mm (88% of the total), was measured on 29 October 1992, after the high autumn discharges.

At profile three, the total upper bank erosion was less than half that at the lower bank, 43mm and 100mm, respectively. Although the contribution to upper bank erosion measured on 24 August 1992 was as much as any other measured at any one time, it was less than the combined contribution from erosion measured for the autumn flow event (that is erosion measured on 27 September and 29 October 1992, see Appendix 4.2). Most of the lower bank erosion at profile three, 67mm, was measured on 27 September during the high autumn flows, with an additional 30mm measured on 29 October 1992.

Between 29 October 1992 and 11 January 1993 there was only 2mm of erosion measured at the upper bank at profile three, whereas the flow was too high to measure exposure of the lower pin. This period included the high winter discharges when flow recorded at the upstream flow gauging station at Staines peaked at $259m^3/s$ on 4 December 1992 (see Appendix 4.5).

Accounting for abstractions between Staines gauging station and the Upper Chertsey monitoring site, this peak discharge in December 1992 would have still been in the order of $250m^3/s$ at Chertsey, since the total average abstraction is less than $4m^3/s$. This is approximately bankfull discharge (Thames Water, 1988a) and compares with a peak autumn discharge recorded at Staines on 27 September 1992 of $130m^3/s$ (52% bankfull).

Plate 4.25 is an upstream view of the monitoring site, taken on 28 September 1992, the day after the peak autumn discharge. The tide line on the bank suggests that the autumn flow peaked at a level somewhat higher (~0.15m) than the water level shown, which is approximately 0.1m below the top of the bank. The winter flood was at approximately bankfull discharge but resulted in no appreciable erosion compared to the autumn flows. It is, therefore, likely that preparatory factors weakened the particles at the surface of the bank material and facilitated the entrainment of material by the autumn flows, but did not act to weaken the bank material prior to the bankfull discharges experienced in the winter of 1992. Neither of the erosion pins could be located in May 1993, but the appearance of the bank suggested that no significant bank erosion had taken place since January 1992 and it is likely that the erosion pins were removed deliberately.

At profile four the water level was too high to measure exposure at either of the pins on 11 January 1993, hence all the erosion recorded on 9 May 1993 was for the period from 29 October 1992. The most upper bank erosion, 41mm, was measured on this date. The lower erosion pin could not be relocated after the high winter flows but the appearance of the bank would suggest that the pin had been deliberately removed. The bank survey (Appendix 4.4) also indicates that no lower bank erosion occurred throughout the monitoring period.

Plate 4.25 Upstream view of the Upper Chertsey site following subsidence of peak autumn flows (28 September 1992).

Plate 4.26 Upstream view of the Upper Chertsey site following subsidence of high winter flows (11 January 1993).

It would appear then, that during the monitoring period upper and lower bank erosion at this site was dominated by the high discharges in 1992. However, the contribution to erosion from factors that weaken the particles on the surface of the bank has also been demonstrated. High, unvegetated banks are prone to desiccation during dry summers and the weakened bank material can be more easily entrained by the flow. In addition, mechanical damage may have resulted from angling at the site (shown in Plate 4.25) and cattle trampling. Indeed, cattle were grazing the site by the visit on 9 May 1993 and, although they appeared to have been responsible for little erosion during the summer of 1992, they may have been responsible for some of the erosion during the 1993 grazing season, after the high winter discharges. However, the contribution to erosion in the spring period was insignificant in profile three, and probably little to do with cattle trampling at profile four. This is because firstly, the bank is just upstream of a vegetated beach (Plate 4.24) which would probably be preferentially accessed by the majority of cattle and, secondly, although hoof prints were observed at the water's edge, there was no disturbance of the material at the foot of the bank to suggest cattle trampling.

Loose material occupied the foot of the steep bank at profiles three and four in May 1993. This may be attributed to crumbs of bank material falling from the face of the bank, probably as a result of wetting and drying cycles early in the year and remaining at the toe without the adequate discharges to facilitate their removal. Hence, some amount of the erosion measured at the pins in profile four on 9 May 1993 could be due to wetting and drying cycles rather than the high winter flows. Although the erosion pin exposure at the upper or lower bank at profile four could not be measured on the 11 January 1993, the crumbling surface of the bank had been smoothed by the high flows.

Section 4.9 reviews the processes and mechanisms of erosion at Upper Chertsey in relation to the other monitoring sites.

4.8 Lower Chertsey

The location of the Lower Chertsey monitoring site, on the left bank downstream of Chertsey Marina, is shown in Appendix 4.1 together with a site plan showing the positions of the bank profiles and erosion pins. Six bank profiles were surveyed along a distance of 44m and erosion pins were installed in the banks at only three of these, because erosion pins at the remaining three profiles may have posed a danger to anglers.

Details of the monitoring site can be found in Appendix 4.1, and shear stress and soil suction measurements taken during the monitoring period are shown in Appendix 4.3. Erosion measured at each of the pins, on each visit, is given in Appendix 4.2 and shown in Figure 4.8. The bank profiles surveyed were upstream and downstream of a section of masonry wall approximately 9m long. The downstream end of the wall can be seen in Plate 4.27, which is an upstream view of the Lower Chertsey monitoring site.

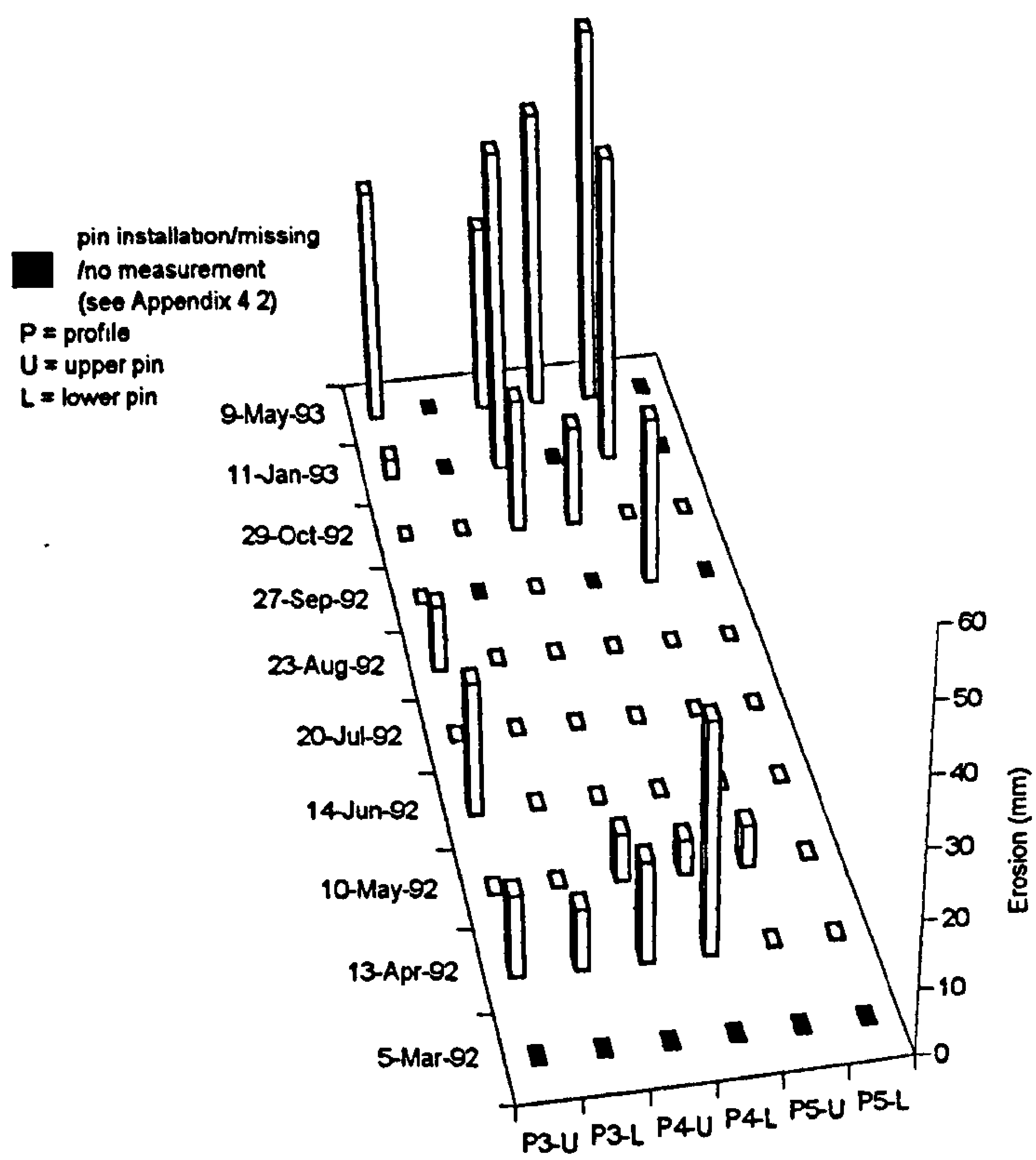


Figure 4.8 Bank erosion measured at Lower Chertsey.

Plate 4.27 Upstream view of the Lower Chertsey monitoring site.

The surveys of the bank at profile one are shown in Appendix 4.4, which shows the gentle slope of the bank down to a pebble beach. The bank remained unvegetated throughout the year. The last survey shows that the most change in the bank was after the winter floods, where the upper bank eroded and there was deposition at the lower bank. The bank surveys taken at profile two are also given in Appendix 4.4 and, again, the most upper bank erosion was between the surveys on 29 October 1992 and 11 January 1993 and there was a build up of material at the lower bank.

The bank at profile three was higher and steeper than at profiles one and two. The erosion measured at the upper and lower pins in profile three is given in Appendix 4.2 and shown in Figure 4.8. The most upper bank erosion measured here in any one visit to the site was 35mm, 44% of the total, which eroded between 11 January and 9 May 1993. Comparable erosion, 37% of the total at the upper bank, was measured for the period between 14 June and 23 August 1992.

Although the upper bank erosion at profile three measured after 23 August 1992 was substantial, and amounted to 48% of the total, the majority of the upper bank erosion was prior to 23 August 1992. It can not be stated categorically what erosion measured on 9 May 1993 resulted from. The bank here is gravelly and has little cohesion in places. In May 1993 there was a substantial amount of loose material at the upper and lower bank which may have crumbled and detached when the high winter discharges subsided.

As at the Upper Chertsey monitoring site, the same cattle graze this site, so erosion at profile three during the spring may have been attributed, at least in part, to cattle trampling. The contribution to erosion from cattle trampling may not be too substantial however, and may be confined mostly to the upper bank because profile three is quite high and steep and would probably not have been accessed by cattle. This is certainly not to say that the cattle could not have accessed here, simply that the bank at the upstream profiles, profiles one and two, were considerably more shallow and observations suggested that these banks were preferentially accessed by the majority of cattle. An additional erosive factor during the spring is frost action, which may well have loosened soil particles particularly where the face of the bank is unvegetated in winter and weakened by the high antecedent flows.

The lower erosion pin at profile three could not be relocated on 9 May 1993. The appearance of the bank however, would suggest that erosion had been minimal over the winter, and the pin may well have been covered by material loosened from the upper bank. Erosion of lower bank was, therefore, dominated by that in spring 1992.

The erosion measured at each of the pins in profile four is also given in Appendix 4.2 and shown in Figure 4.8. In total there was slightly more erosion at the upper bank than at the lower, 118mm compared to 99mm, respectively. The most upper bank erosion measured at one time was 48mm, 41% of the total, during the period from 29 October 1992 to 11 January 1993. An additional 20mm of upper bank erosion was measured on 29 October, for the period from 27 September 1992. By this September visit, as mentioned in relation to the Upper Chertsey monitoring site, the high autumn flow had already peaked and no erosion of the upper bank had occurred since 23 August. For the upper bank erosion to then occur, when levels had already dropped to below the level of the upper pin, would imply that the flow only weakened the bank material and failure then resulted from drawdown of the water surface after the high flows had subsided. The failure of a further 48mm of the upper bank suggests that the autumn flows and subsequent drawdown had weakened the bank material sufficiently for the high winter flows to then result in erosion.

At profile four, the combined contribution to upper bank erosion during both the spring periods of 1992 and 1993 was 42%, compared to a contribution of 58% for the autumn and winter periods combined. However, the effect of the high winter discharges on the amount of lower bank erosion subsequent to 11 January 1993 is unknown as, once again, the high flow on 11 January 1993 prevented the measurement of exposure at the lower pin. However, erosion measured on 9 May 1993, for the period from 29 October 1992, was 46% of the total and bank surveys in Appendix 4.4 suggest that there was erosion prior to the survey in January 1993. This would suggest that at profile four lower bank erosion was dominated by the high discharges although a significant contribution to the total erosion was during the spring period of at least 1992, and perhaps also 1993. It was somewhat surprising to see no erosion at the upper or lower pins during the summer period. The bank did become partially vegetated during the summer, but there were also signs of desiccation and crumbling at the face of the bank.

No lower bank erosion was recorded at profile five, as shown in Figure 4.8, but the high flow in January 1993 did not permit measurement for the period from 29 October 1992, and the erosion pin could not be relocated in May 1993. However, from the appearance of the profile in May 1993 and the survey taken 11 January 1992, the pin may well have been buried.

There was more erosion measured at the upper bank at profile five than was measured at any of the other five erosion pins at this site. The contribution to erosion during the spring 1992 period was substantially less than that measured during the spring 1993 period, which amounted to 42% of the total. The erosion measured after the high lows in 1992 contributed the remainder of the total, with 19% measured on 27 September 1992, and 34% on 11 January 1993, but no erosion of the upper bank measured on 29 October 1992. This would suggest that either the autumn flows that peaked the day before the visit on 27 September removed all the available bank material, or that failure due to drawdown occurred within one day, or a combination of both. The lower bank may have had a sufficient covering of vegetation to prevent erosion during the high autumn flows and received deposition from the upper bank some time prior to the May 1993 visit.

The surveys of the bank taken at profile six are shown in Appendix 4.4. This profile, along with profiles one and two did not have erosion pins installed. The bank at these profiles was assumed to be accessed by anglers, although no anglers were seen at the site (mindful of the fact that the site was visited less than a dozen times throughout the monitoring period). However, there was evidence of cattle trampling the banks to access the water's edge from the pebble beach, and the bank surveys clearly show the quite dramatic changes in the profile through the monitoring period. The erosion can not be categorically attributed to any individual cause, nonetheless, the pattern does suggest that upper bank material failed between March and July 1992 and was deposited at the lower bank. The removal of some of this material between July and the end of October 1992 was followed by further upper bank erosion with lower bank deposition up to the final survey in January 1993.

The processes and mechanisms of erosion at Lower Chertsey in relation to the other monitoring sites are reviewed in Section 4.9, below.

4.9 Review of bank erosion monitoring

The use of pins to monitor bank erosion proved to be a relatively successful technique. However, on some occasions erosion at the pins could not be measured because of high flows or vegetation, for example (see Appendix 4.2). Soil samples were taken from each site on only one occasion during the monitoring period, hence analysis proved to be heavily dependent on conditions prior to sampling. During winter, low banks were often saturated and, as expected, showed a comparatively high moisture content. In order for the engineering properties of the bank material to be correlated to bank erosion, analysis incorporating sampling on a more continuous basis would have been more appropriate through the inclusion of temporal variation. Furthermore, monitoring of soil suction and shear strength was hampered by frequent equipment failure. Consequently, the visual appearance of the bank material and it structure provided the most useful insight into the processes and mechanisms of erosion.

As discussed in Chapter Two: Approach and Methodology, evidence of substantial historical changes in character of the bank was established from dated paintings and photographs. At the beginning of the 20th Century, marginal vegetation was more prolific along the Thames, particularly at the Lower Wallingford and Goring monitoring sites. Whilst no definitive conclusions regarding the processes and mechanisms of erosion can be drawn from this evidence, the author believes that dredging of the river during this century has contributed to the decline of marginal vegetation (Bonham, 1983) and lowering of the level of the water surface. In turn, this will tend to increased flow velocities at the toe of the bank and the exposure of the bank to boat wash.

The previous sections detailed the specific processes and mechanisms of bank erosion at each individual monitoring site. This section combines the observations from each of the monitoring sites to discuss the various processes and mechanisms of erosion and the factors influencing them.

Whereas the erosion measured at each of the erosion pins was shown in Figures 4.2 to 4.8 for each monitoring site in turn, Appendix 4.2 also includes (in brackets) an estimate of bank erosion when the pins could not be located. Inclusion of this estimated erosion is particularly significant for the Laleham site where the erosion pins were eroded. Appendix 4.2 therefore includes an additional 500mm of erosion at the upper and lower pins at Laleham. Further estimates of erosion are also included for the St. John's monitoring site and also Lower Wallingford which experienced undercutting of the lower pins at profiles three and four. Using these estimates, Figure 4.9 shows the average rate of erosion at each erosion pin.

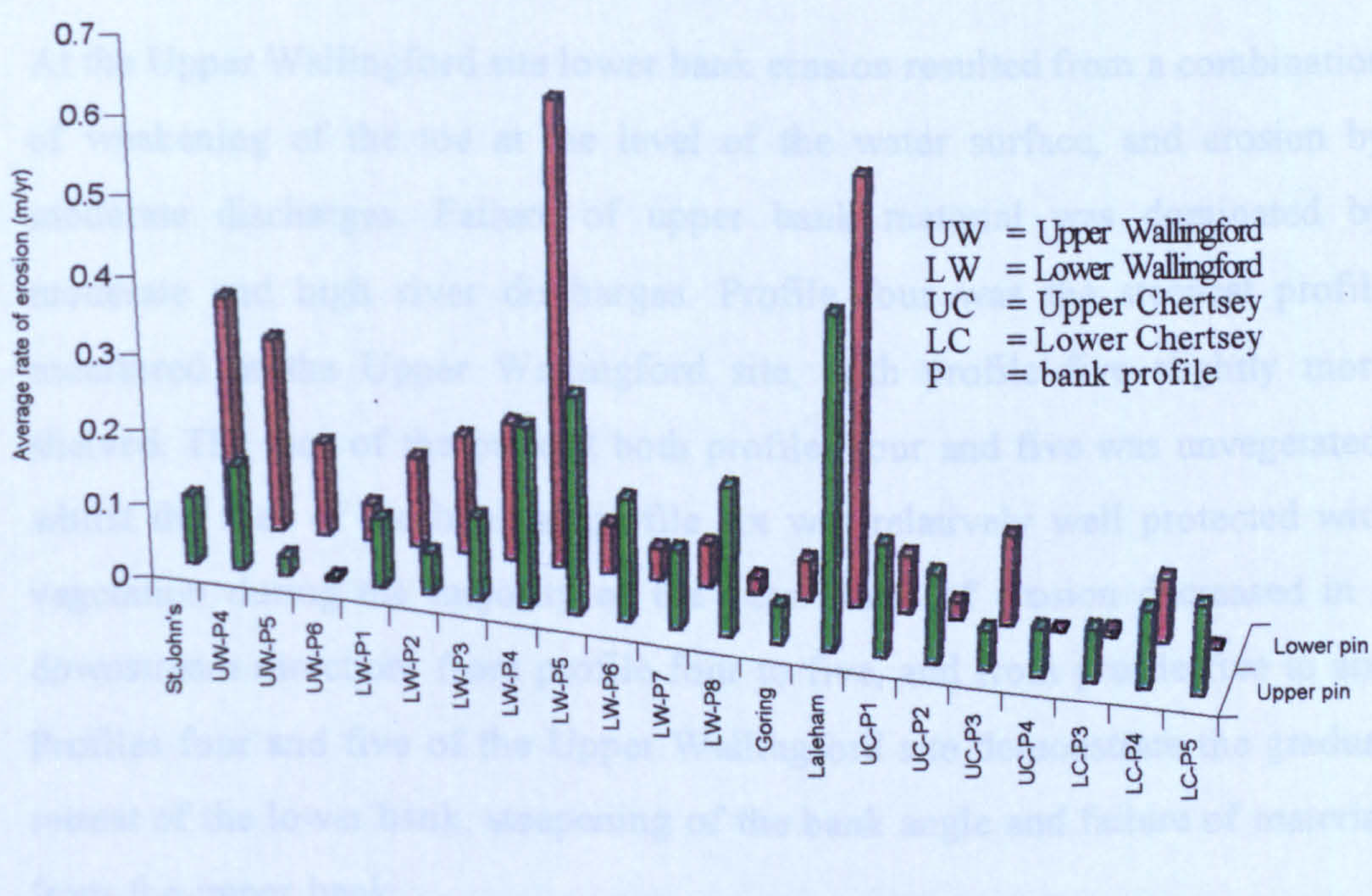


Figure 4.9 Average rate of erosion measured at each pin.

Figure 4.9 shows higher rates of erosion at the lower bank than the upper bank at St.John's, Laleham, Upper Wallingford, the first four profiles (profiles one to four) of the Lower Wallingford site and profile three of the Upper Chertsey site. Rates of upper and lower bank were roughly equal at Goring, and rates of upper bank erosion exceeded lower bank erosion at the ten remaining profiles.

The rate of lower bank erosion at St. John's was more than three times the rate of upper bank erosion. Cattle trampled both the upper and lower bank but, whereas the lower bank remained saturated throughout the monitoring period, the surface of the upper bank hardened during summer desiccation. Therefore, it may be that the upper bank remained more resistant to mechanical damage and compaction than the saturated lower bank material. Further reasons may be the curvature of the bend encouraging higher velocities at the toe of the bank, and the gently sloping bank which will reduce velocities higher up the bank.

At the Upper Wallingford site lower bank erosion resulted from a combination of weakening of the toe at the level of the water surface, and erosion by moderate discharges. Failure of upper bank material was dominated by moderate and high river discharges. Profile four was the steepest profile monitored at the Upper Wallingford site, with profile five slightly more shelved. The face of the bank at both profiles four and five was unvegetated, whilst the face of the bank at profile six was relatively well protected with vegetation during the majority of the year. Rates of erosion decreased in a downstream direction: from profile four to five, and from profile five to six. Profiles four and five of the Upper Wallingford site demonstrate the gradual retreat of the lower bank, steepening of the bank angle and failure of material from the upper bank.

At Lower Wallingford the rate of lower bank erosion exceeded upper bank erosion at the four upstream profiles (profiles one to four), whereas the opposite was observed at the most downstream profiles (profiles five to eight). Lower bank erosion was particularly associated with weakening and weathering of the clay toe by undercutting at the sandy layer below the clay. Failure and removal of the weakened clay wedges followed under moderate and high discharges. It is worth noting that whilst the rate of upper bank erosion at the four downstream profiles remained comparable to that at the four upstream profiles, the rate of lower bank erosion the was substantially lower at the four downstream profiles. This may be due to a combination of two factors. Firstly, The monitoring site is immediately downstream of Wallingford Bridge (see Appendix 4.1) and it may be that the throttling effect of the bridge is experienced more by the first four upstream profiles than by the last four. Secondly, the toe of the bank at the four downstream profiles remained below the surface of the water and, therefore, escaped much of the weakening and weathering processes experienced at the toe of the four upstream profiles.

At Goring, upper and lower bank erosion rates were similar and low compared to rates of erosion at other sites. Erosion resulted from a combination of weakening and weathering and fluvial entrainment during moderate and high flows. At Laleham erosion rates at the upper and lower bank were high and weakening and undercutting of the low, sloping bank resulted in erosion of the root zone material during high flows.

Rates of erosion at the Upper and Lower Chertsey sites were relatively low compared with the Wallingford sites where the banks were similar in height and angle. The bank material at the Upper Chertsey monitoring site was relatively sandy, whereas the banks at Lower Chertsey were more gravelly. Whilst the Chertsey monitoring sites did not completely escape the effects of weakening and weathering processes, erosion was generally attributed to moderate and high flows.

Taking an average value of the erosion at the upper and lower pins at each site, Table 4.2 compares the average rates of erosion at the upper and lower banks. The numbers in brackets indicate averages derived from incorporating estimates of erosion when pins could not be located, as described above (see Appendix 4.2). Figure 4.10 illustrates the data in Table 4.2, using the estimates shown in brackets.

Table 4.2 Average rates of bank erosion at each monitoring site.

Monitoring site	**Average erosion rate (m/yr)**	
	Upper bank	**Lower bank**
St. John's	0.021 (0.093)	0.184 (0.312)
Upper Wallingford	0.056	0.148
Lower Wallingford	0.157	0.122 (0.160)
Goring	0.050	0.054
Laleham	0.007 (0.431)	0.130 (0.555)
Upper Chertsey	0.094	0.055
Lower Chertsey	0.094	0.031
Average of all sites:	0.068 (0.139)	0.103 (0.188)

Note: numbers in brackets are derived using estimates of erosion (see Appendix 4.2)

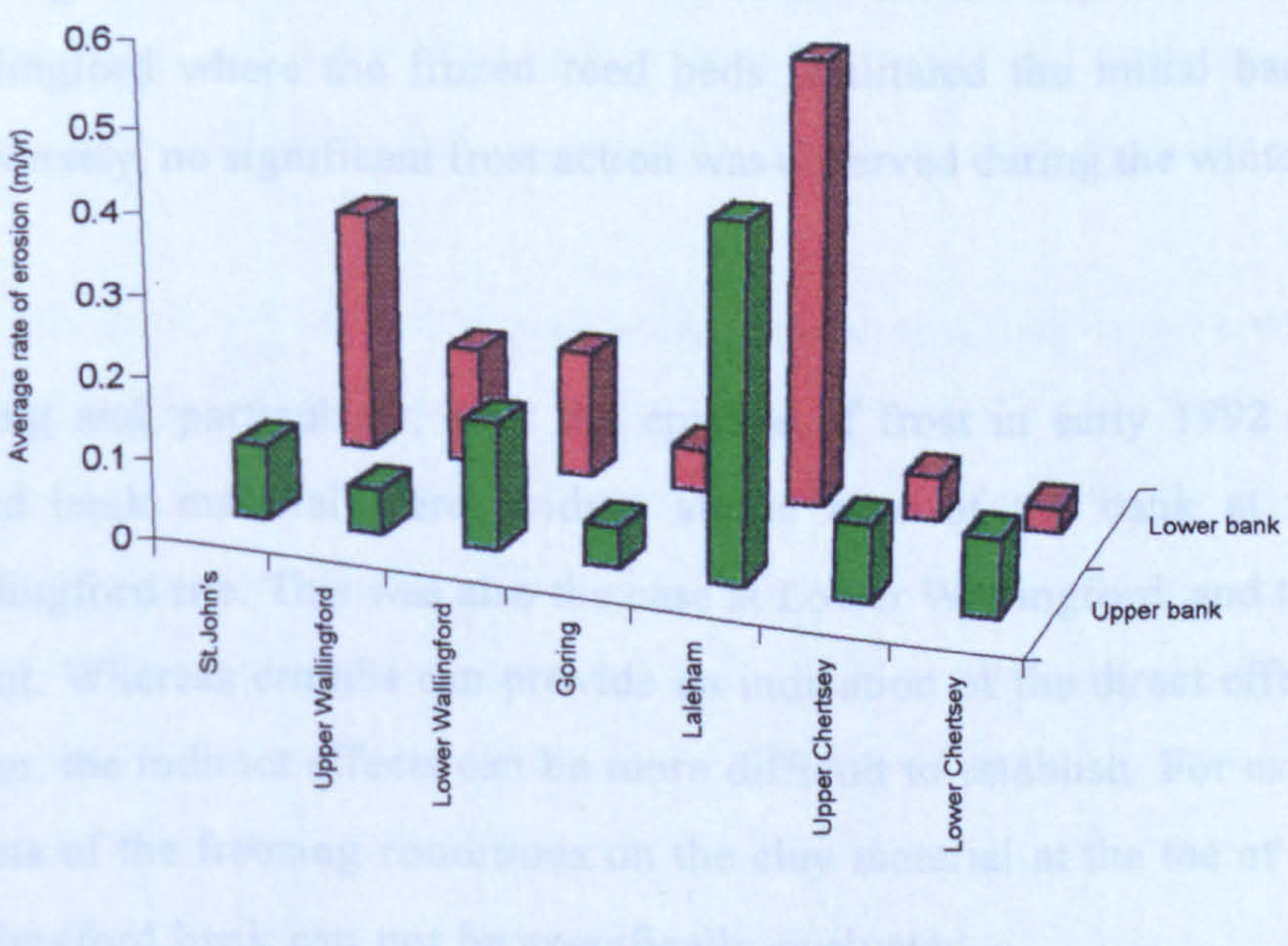


Figure 4.10 Average rate of upper and lower bank erosion at each monitoring site.

In broad terms, there were three mechanisms of erosion observed during the monitoring period: (1) weakening and weathering, (2) fluvial entrainment and (3) slumping. These mechanisms did not act in isolation to result in bank erosion and were influenced by numerous factors including river discharge, bank material and geometry, temperature, vegetation and the use of the bank. Table 4.3 shows the average percentage of upper and lower bank erosion at each site that can be attributed to the various erosion mechanisms. Appendix 4.2 shows what erosion was attributed to each mechanism at each site. The various mechanisms of erosion are reviewed below.

Weakening and weathering:

The first weakening process observed during the monitoring period was frost action and needle ice at the beginning of the monitoring period (January 1992). Needle ice appeared to be more significant where the flow was particularly still and where the water inundated the bank over a relatively large surface area. For example, the spending beach at profile one of the Lower Wallingford site allowed ice formation over the surface of the lower bank where the water level fluctuated (see Plate 4.10). At Goring the still water behind the reed bed allowed the surface of the water to freeze over (see Plate 4.20). Surface freezing was also observed at the St. John's monitoring site and at Upper Wallingford where the frozen reed beds facilitated the initial bank survey. Conversely, no significant frost action was observed during the winter of 1992-93.

During and, particularly, after the episode of frost in early 1992 crumbs of failed bank material were evident at the base of the bank at the Upper Wallingford site. This was also the case at Lower Wallingford, and to a greater extent. Whereas crumbs can provide an indication of the direct effect of frost action, the indirect effects can be more difficult to establish. For example, the effects of the freezing conditions on the clay material at the toe of the Lower Wallingford bank can not be specifically evaluated.

No specific frost or ice action was observed at the other sites during the monitoring period. This is because of two reasons. Firstly, the only sites visited early in 1992, when frost was observed, were Goring and Upper and Lower Wallingford. Secondly, the parts of the lower bank at the Upper and Lower Wallingford sites are shelved and remained above the water level during the frost episode. Weakened crumbs falling from the surface of the material could therefore accumulate on the shelves. Alternatively, where the lower bank was submerged, such as at Goring, weakened crumbs would fall into the water below and escape observation. Because frost action was only observed at three sites, unequivocal conclusions can not be drawn regarding the influence of bank height and material on the effectiveness of frost and ice. However, since freezing pore water tends to reduce the cohesive strength of soils, it is likely that banks comprised of cohesive materials will be more susceptible to erosion from frost action than their less cohesive counterparts. Bank vegetation was also observed to influence the effect of frost action. For example, at the Goring and Wallingford monitoring sites, where the most significant frost action was observed, the bank vegetation was sparse during the colder winter months, whereas at the Upper Wallingford site, where the banks had some vegetation cover, the effects of frost action were notably less. It is estimated that at Upper Wallingford, frost action contributed 19% to the total upper bank erosion, but resulted in no erosion of the lower bank. The contribution to upper and lower bank erosion at Lower Wallingford was 4% and 10%, respectively, which increased to 23% and 74%, respectively, at Goring (see Table 4.3).

The effects of wetting and drying cycles on the structure of the bank material was most evident at the Lower Wallingford monitoring site. The bank here is relatively high (~1.5m - 2m) and separate soil horizons within the bank material can be easily distinguished. Plate 4.12 shows a dark, organic root zone some 20cm - 30cm deep, which overlies a thin gravel layer approximately 10cm thick. Below this is a more sandy layer of material approximately 60cm thick which, in turn, overlies the clayey lower bank approximately 60cm thick. The clay at the toe of the bank can be seen overlying a sandy beach in Plate 4.14.

Processes of wetting and drying at the Lower Wallingford site were most evident within the root horizon at the top of the bank and at the clay layer at the lower bank. Typically during the summer, the soil structure desiccated leaving loosened soil aggregates held together by the effective cohesion of the fibrous roots at the upper bank. This leaves the material at the surface of the root zone more susceptible to failure under gravity or subsequent high discharges, or removal by mechanical means, for example when accessing the bank for amenity.

During the summer, when flows were relatively low, the toe of the bank at Lower Wallingford was at, or just above, the surface of the water in some places. The increase in tensile stress due to a combination of wetting and drying cycles and boat wash at the low summer water level resulted in tension cracks at the toe of the bank. The cracks developed in the clay parallel to the face of the bank and resulted in the vertical shearing of small wedges of clay approximately 10cm size (see Plate 4.14). Whilst shearing occurred during the low flows, the failed clay wedges tended to remain almost in their original position until a moderate flow removed them from the base of the bank. Moderate flows subsequent to these wetting and drying processes also resulted in direct erosion of the lower bank (see below). The appearance of the lower bank after the monitoring period indicated that the clay toe had also experienced this vertical shearing during the summer of 1993 (see Plate 4.28).

Plate 4.28 Shearing of the clay toe at Lower Wallingford (September 1993).

The effects of wetting and drying were obviously reduced where the water level remained more constant. For example, at the most downstream profiles at Lower Wallingford the clay toe remained submerged throughout the monitoring period and no obvious failure of the toe was observed.

The presence of bank vegetation in places at the Upper Wallingford site reduced the effect of wetting and drying cycles. Desiccation cracks were also observed at St.John's on the top of the bank where vegetation was sparse. The unvegetated bank face at Goring also suffered from wetting and drying during the summer but to a lesser extent than the banks at the Wallingford sites. This is mostly likely because the bank height at Goring is relatively low (<0.5m) so that moisture conditions through the bank material were retained more favourable than at the higher banks at the Wallingford sites.

The effects of wetting and drying cycles appeared to be less where bank material was more sandy or gravelly, such as at Upper and Lower Chertsey. This reflects the resistance that non-cohesive particles have to wetting and drying cycles, compared to the shrinkage and swelling experienced by clayey, cohesive materials under similar regimes. Table 4.3 shows the significant influence of wetting and drying cycles on erosion at the Upper and Lower Wallingford sites and the Lower Chertsey site.

Other specific weakening and weathering processes observed during the monitoring period include cattle trampling at St. John's and recreational access at the Lower Wallingford monitoring site. No erosion measured at the Lower Wallingford site could be specifically attributed to recreational access alone, it is, therefore, difficult to determine its influence on erosion. However, at St. John's a significant amount of erosion was attributed to cattle trampling banks: at least 78% and 41%, respectively, of the total upper and lower bank erosion (see Table 4.3).

Fluvial entrainment:

Erosion due to fluvial entrainment resulted from a variety of flow discharges. The effectiveness of the flow to entrain material often depended on the amount of weakened material at the surface of the bank. Typically, prior to erosion, the material on the surface of the bank comprised loose crumbs. These crumbs were then removed by flows to leave the smooth surface observed after erosion events. During the monitoring period there were four episodes during which river discharge was observed to result in fluvial entrainment. The timing of these flows was as follows:

1: April 1992: low spring flows (<50% bankfull)

2: September 1992: moderate autumn flows (>50% but < 100% bankfull)

3: November 1992 - January 1993: high winter flows (~ bankfull)

4: April 1993: moderate spring flows (>50% but < 100% bankfull)

The results from the monitoring programme provide some indication of the effects on bank erosion of the first three flows listed above. However, erosion measured after the April 1993 flow also includes erosion due to any weakening and weathering that may have occurred since January 1993 (see Table 4.3).

At several sites the low spring flows were relatively effective at removing bank material. The peak flow in April 1992 appeared to be most pronounced at St. John's where it was comparable to the peak flow experienced in September 1992. The influence of the April 1992 peak diminished downstream so that, at the remaining monitoring sites, the April 1992 discharge was approximately 50% of that in September 1992. The most erosion to result from the April 1992 flow was at the lower bank at Lower Wallingford, although this constituted only 11% of the total lower bank erosion. The highest proportion of erosion was at the Lower Chertsey site, where the April 1992 flow resulted in 40% of the total lower bank erosion. (see Table 4.3).

The moderate flows in September 1992 resulted in erosion of the upper and lower banks at several of the sites. At St. John's the September 1992 flow resulted in 41% of the total lower bank erosion. This contribution to lower bank erosion was reduced to nearly 19% at Upper Wallingford but 33% of the total upper bank erosion was recorded after this event. Erosion resulting from the September flows was greatest at Lower Wallingford, although it contributed only 13% and 14% of the upper and lower bank erosion, respectively. The most significant contribution to erosion was at Upper Chertsey where the September peak resulted in 48% and 75% of the total upper and lower bank erosion, respectively (see Table 4.3).

Table 4.3 Percent contribution from various erosion mechanisms to average rates of upper and lower bank erosion at each site.

Erosion processes and mechanisms	Percent contribution to erosion at each monitoring site.						
	SJ	UW	LW	GR	LA	UC	LC
River flow							
April 1992:							
Upper bank	0	1	5	14	2	N/A	8
Lower bank	5	9	11	0	6	N/A	40
September 1992:							
Upper bank	14	33	13	12	0	48	14
Lower bank	41	19	14	4	0	75	14
Winter 1992-93:							
Upper bank	0	38	16	35	98	28*	29
Lower bank	4	2	19	7*	76	15*	42*
Total erosion due to flow:							
Upper bank	**14**	**72**	**34**	**61**	**100**	**76***	**51**
Lower bank	**50**	**30**	**44**	**11***	**82**	**90***	**96***
Miscellaneous (river flow)							
April 1993:							
Upper bank	N/A	6	11	6	N/A	28*	36
Lower bank	N/A	11	18	7*	N/A	15*	42*
Wetting and drying cycles							
Upper bank	8	1	35	9	0	24	13
Lower bank	9	35	29	14	17	10	5
Frost and needle ice							
Upper bank	N/A	22	4	23	N/A	N/A	N/A
Lower bank	N/A	0	10	74	N/A	N/A	N/A
Cattle 'poaching'							
Upper bank	78	N/A	N/A	N/A	N/A	N/A	N/A
Lower bank	41	N/A	N/A	N/A	N/A	N/A	N/A

Note: * denotes where erosion resulted from a combination of two erosion process.
ST=St.John's, UW=Upper Wallingford, LW=Lower Wallingford, GR=Goring, LA=Laleham, UC=Upper Chertsey, LC=Lower Chertsey.

The high winter flows from November 1992 through to the end of January 1993 meant that some erosion pins could not be measured. Consequently, erosion measured after the flows had subsided will be a result of the high flows and any other additional weakening mechanisms subsequent to the high flows. Table 4.3 and Appendix 4.2 identify where erosion is a result of more than one specific flow event, such as at the lower bank at Goring, the upper and lower bank at Upper Chertsey and the lower bank at Lower Chertsey.

The high winter flow had the most influence on erosion at Laleham, where the pins were eroded. The winter flows also resulted in 35% of the upper bank erosion at Goring and 38% of the upper bank erosion at Upper Wallingford. Combined with the erosion measured in May 1993, the high flows also made a substantial contribution to erosion at Upper and Lower Chertsey, although erosion measured in May 1993 will include any influence due to weakening and weathering processes prior to May 1993 (see Table 4.3).

Slumping:

Failure of the upper bank by slumping was only observed at the Lower Wallingford site. Whereas none of the profiles monitored showed significant slumping, failed upper bank material was observed at the toe of the bank after the high September 1992 flows had subsided (see Plate 4.16). Although no significant failures were observed during the monitoring, the continued undercutting at the toe of the bank after the monitoring period (see Plate 4.28) resulted in significant upper bank failure in the end of summer 1993 (see Plate 4.29).

Using the average erosion rates at the upper and lower bank at each site, Figure 4.11 illustrates the proportion of erosion attributed to the various processes and mechanisms discussed above.

Plate 4.29 Bank failure at Lower Wallingford at the end of summer 1993.

The most influential erosion processes during the monitoring period were wetting and drying, the moderate flows in September 1992 and the high flows in winter 1992-93. In addition, cattle poaching and frost action had a significant influence at St. John's and Goring, respectively. However, Figure 4.11 does not show the contribution to erosion from the significant undercutting and slumping observed at the Lower Wallingford site after the monitoring period (see Plates 4.28 and 4.29). It may be that scale of slumping observed at the end of summer 1993 occurs only every few years and only after the lower bank has eroded sufficiently to undercut the upper bank. The size of the failed blocks in Plate 4.29 suggests that such failure can result in approximately 0.5m of bank retreat. Averaged over three years, this would equate to a rate of approximately 0.16m per year due to slumping. This would double the erosion rate and make slumping the most significant erosion mechanism at the Lower Wallingford site.

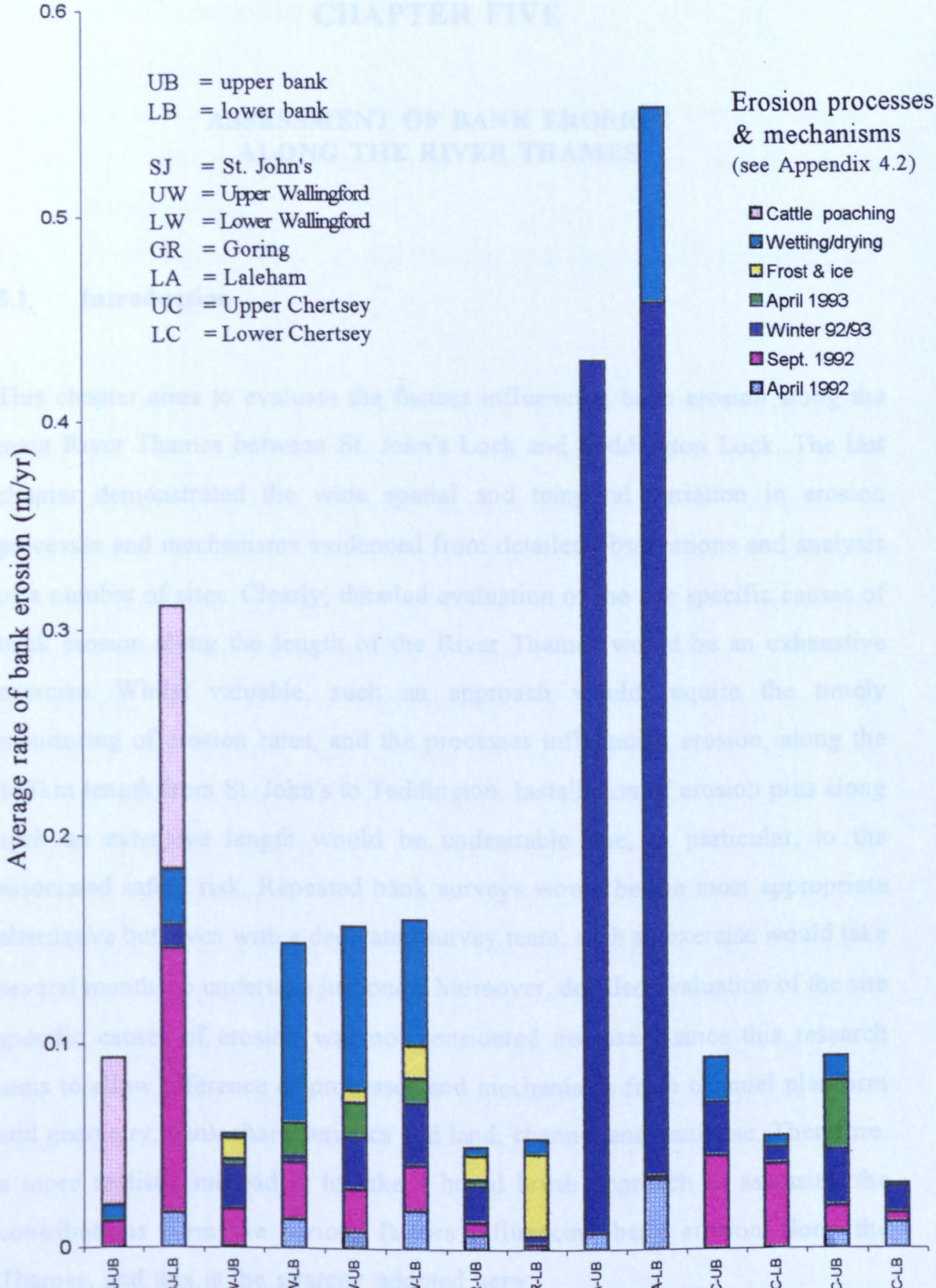


Figure 4.11 Rates of upper and lower bank erosion attributed to various processes and mechanisms.

CHAPTER FIVE

ASSESSMENT OF BANK EROSION ALONG THE RIVER THAMES

5.1 Introduction

This chapter aims to evaluate the factors influencing bank erosion along the main River Thames between St. John's Lock and Teddington Lock. The last chapter demonstrated the wide spatial and temporal variation in erosion processes and mechanisms evidenced from detailed observations and analysis of a number of sites. Clearly, detailed evaluation of the site specific causes of bank erosion along the length of the River Thames would be an exhaustive exercise. Whilst valuable, such an approach would require the timely monitoring of erosion rates, and the processes influencing erosion, along the 143km length from St. John's to Teddington. Installation of erosion pins along such an extensive length would be undesirable due, in particular, to the associated safety risk. Repeated bank surveys would be the most appropriate alternative but, even with a dedicated survey team, such an exercise would take several months to undertake just once. Moreover, detailed evaluation of the site specific causes of erosion was not considered necessary since this research aims to allow inference of processes and mechanisms from channel planform and geometry, bank characteristics and land, channel and bank use. Therefore, a more realistic method is to take a broad brush approach in assessing the contributions from the various factors influencing bank erosion along the Thames, and this is the strategy adopted here.

The analysis presented here is derived from a combination of studies, surveys and assessments which are discussed in detail in Chapter Two: Approach and Methodology.

There are two main components to this analysis:

i) a reach scale assessment of factors influencing bank erosion along the River Thames, including stream power, boat traffic and river bank characteristics;
ii) an assessment of factors contributing to erosion at 147 sites along the River Thames;

Table 5.1 summarises the aspects considered within each of these components. Clearly, not every factor that could conceivably influence bank erosion along the River Thames has been assessed. The most notable of those omitted from the assessment are factors that contribute to the weathering of bank material, such as wetting/drying cycles and freeze/thaw. These influences are considered indirectly through the influence of bank geometry and vegetation cover on the susceptibility of the bank to erosion processes. Water chemistry can also influence bank erosion, and particularly the difference in the ionic concentrations between the river water and the pore water within the bank material. No consideration is given to water chemistry in this assessment since analysis of hundreds of samples of river water and soil pore water would be required on a continuous basis to identify any changes in chemistry that could contribute to bank erosion. Furthermore, the outputs from such an analysis would probably be of little value because changes in river water and pore water chemistry will tend to be directly associated with changes in river flow and the pore water pressures within the bank material, making separation of the contribution to erosion from the two factors impossible.

Nonetheless, the evaluation does provide an overview of the main contributing factors, including aspects found to influence erosion at the monitoring sites discussed in the last chapter.

Table 5.1 Aspects evaluated in the assessment of bank erosion along the River Thames.

Influences on bank erosion	**Parameters evaluated and source of information**
Component 1: Factors influencing bank erosion along each reach of the River Thames	
Discharge and slope:	Stream power per unit bed width (W/m^2), measured at bankfull discharge, derived from Thames Water hydraulic model[1] and Thames Conservancy (1965). Bank shear stress (N/m^2), at high flow, derived from near-bank velocity measured at ~ 60% bankfull discharge.
Channel planform and geometry:	Reach sinuosity: the ratio of the centreline channel length to the length along the valley axis, measured from British Geological Survey maps[2].
River bank characteristics:	Flow deflection potential: a measure of the proportion of hard bank protection, derived from the RTBS[3]. Bank erosion susceptibility: evaluation of the extent of intact and failing hard bank protection and, where unprotected, the extent of different types of bank vegetation, as indicators of the bank's susceptibility to erosion, derived from the RTBS[3].
Land, channel and bank use:	Characterisation of boat wash generated along the Thames from boat wash monitoring, and determination of the potential for wash to cause bank erosion. Boat wash impact potential: average number of craft per metre channel width per year, derived from boat traffic statistics[4] and Thames Conservancy (1965).
Component 2: Factors influencing bank erosion at 147 sites along the River Thames	
Factors in erosion Group A:	Length of bank at sites where erosion is influenced by factors related to channel planform and geometry, including bank geometry, and flow deflection from structures within the channel. Derived from the RTBS[3].
Factors in erosion Group B:	Length of bank at sites where erosion is influenced by factors related to land and bank use, including activities such as angling, livestock grazing and pedestrian access, but not those related to navigation. Derived from the RTBS[3].
Factors in erosion Group C:	Length of bank at sites where erosion is influenced by factors related to navigation, such as lock operations, mooring and activities generating boat wash. Derived from the RTBS[3].

Notes:
1. Thames Water 1987, 1988a-d;
2. Geological Survey of Great Britain (1:50 000 series) Sheets 236, 252, 253, 254, 255, 268, 269 and 270;
3. RTBS: River Thames Bank Survey, Volume II of this thesis (NRA 1993);
4. Boat traffic statistics from 1990 - 1996 (courtesy of the Environment Agency, Thames Region).

The bank erosion assessment presented here has also used to produce a stand alone document entitled The River Thames Reach Assessment, which is discussed in detail in Chapter Seven. A copy of the document is presented as Volume III of this thesis.

5.2 Discharge and slope

As a lowland watercourse, the River Thames has a relatively low slope and receives moderate rainfall. Of equal consequence to the natural regime, however, is the regulation of flow for flood defence and navigation, which employs a series of locks and weirs. Evaluation of the effect of discharge and slope (and factors that influence them, such as catchment drainage) has concentrated on the analysis of stream power at a discharge of about bankfull. Flow information was derived from a series of hydraulic sub-models developed to describe the flow conditions along each reach of the River Thames (Thames Water 1987; 1988a-d). An account of the derivation of the data presented here is given in Chapter Two: Approach and methodology.

Figure 5.1 shows the stream power per unit bed area along each reach of the River Thames from St. John's Lock to Teddington Lock (data from which this was derived is given in Appendix 5.1). As expected for a lowland river, stream power along the impounded reaches is relatively low, often several orders of magnitude less than that of upland rivers (refer to Figure 3.3), and certainly less than the $35Wm^{-2}$ considered the threshold for morphological adjustment through erosion (Brookes, 1988). Indeed, historical evidence suggests that natural changes in planform and geometry have not been significant although, in the upper reaches, the Thames has apparently migrated across its floodplain over decades (Bass and Collett, undated).

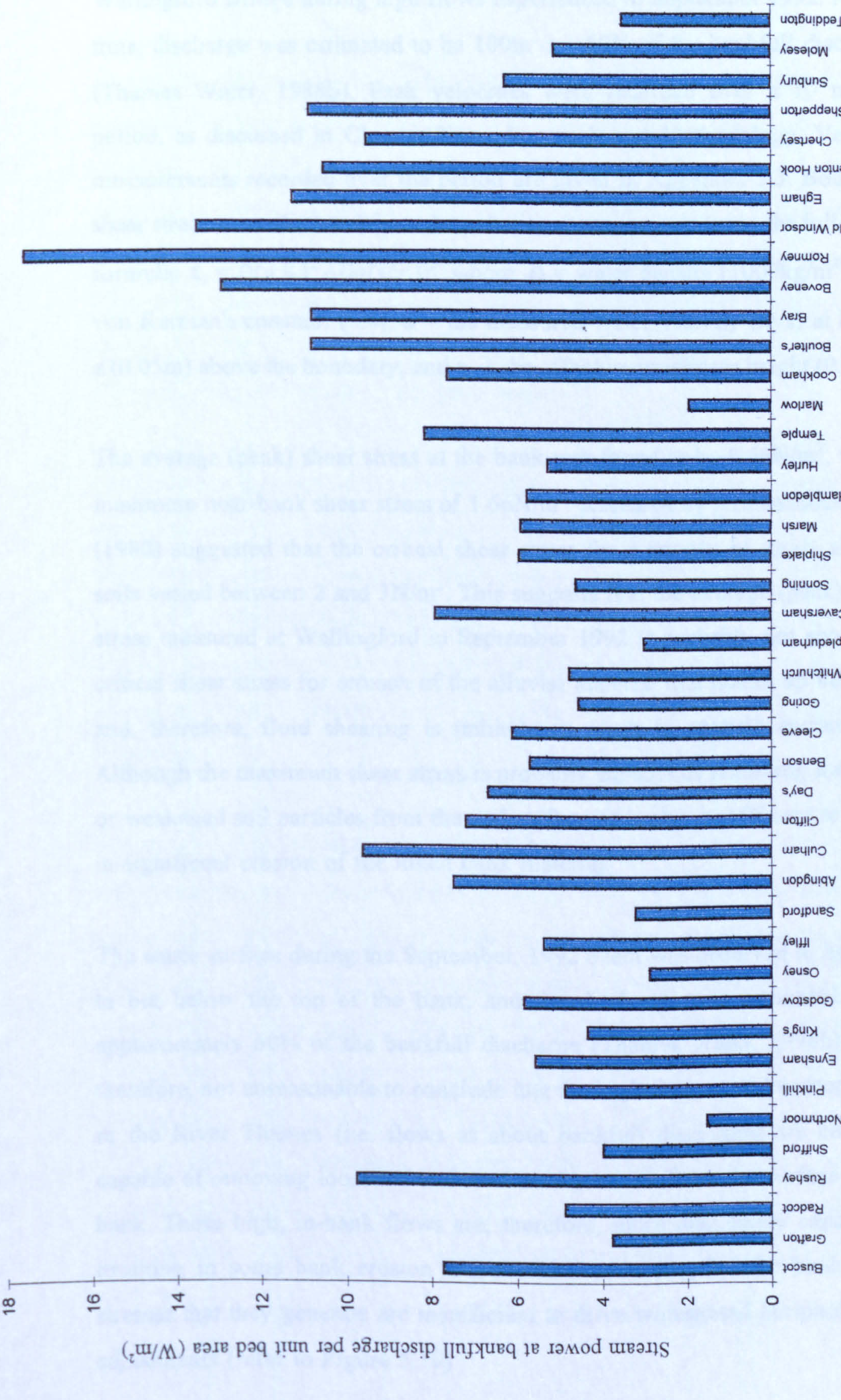


Figure 5.1 Stream power (at bankfull discharge) per unit bed area along each reach of the River Thames.

Flow velocities generated close to the bank were measured downstream of Wallingford Bridge during high flows experienced in September 1992. At this time, discharge was estimated to be $100m^3/s$, ~60% of the bankfull discharge (Thames Water, 1988b). Peak velocities were recorded over a 10 minute period, as discussed in Chapter Two: Approach and Methodology. Velocity measurements recorded over the period are given in Appendix 5.3. Boundary shear stress was calculated from the velocity measurements using the following formula: $\tau_b = \rho(u.K)^2 / (\ln(z/z_o))^2$, where, ρ = water density ($1000kg/m^3$), K = von Karman's constant (0.4), u = the measured water velocity (m/s) at height z (0.05m) above the boundary, and z_o is the effective roughness height (0.01m).

The average (peak) shear stress at the bank was found to be $0.66N/m^2$, with a maximum near-bank shear stress of $1.66N/m^2$. Research by Arulanandan *et al.* (1980) suggested that the critical shear stress for a variety of intact alluvial soils varied between 2 and $3N/m^2$. This suggests that the average (peak) shear stress measured at Wallingford in September 1992 is probably not above the critical shear stress for erosion of the alluvial material that makes up the bank and, therefore, fluid shearing is unlikely to result in particle entrainment. Although the maximum shear stress is probably capable of removing loosened or weakened soil particles from the soil surface, it is also insufficient to result in significant erosion of the intact bank material.

The water surface during the September, 1992 event was observed to be close to but below the top of the bank, and the discharge was estimated to be approximately 60% of the bankfull discharge (Thames Water, 1998b). It is, therefore, not unreasonable to conclude that the high autumn and winter flows in the River Thames (i.e. flows at about bankfull discharge) are certainly capable of removing loosened and weakened particles from the surface of the bank. These high, in-bank flows are, therefore, more than likely capable of resulting in some bank erosion at vulnerable locations, but the bank shear stresses that they generate are insufficient to drive widespread morphological adjustments (refer to Figure 5.10).

5.3 Channel planform and geometry

Clearly the Thames is not a particularly dynamic river with regard to its potential for reach scale morphological adjustment through erosion processes. However, this does not preclude fluvial processes from contributing to morphological changes where local conditions produce a concentration of shear stresses or stream power sufficient to drive erosion and bankline recession. Changes in channel planform and geometry can induce higher boundary shear stresses locally and result in site-scale bank erosion, as discussed in Chapter Three: Factors influencing river bank erosion.

Sinuosity is a measure of the deviation of the course of the river channel from the valley axis and it can, therefore, be used to quantify the degree of stream meandering. Chapter Two discusses the measurement of this parameter, on the basis of the channel routes and valley axis. Sinuosity for each reach of the Thames is shown in Figure 5.2, and is found to range between 1.0 along the Goring and Cleeve Reaches to 1.47 along Godstow and Chertsey Reaches (see Appendix 5.1).

Evaluation of the influence of channel geometry on bank erosion and stability would conventionally be undertaken by assessing the changes in channel cross section along the River Thames. Such an analysis would be based on regime theory and relies on the intimate relationship between discharge, sediment supply, slope and channel dimensions. However, since the River Thames has a regulated flow regime and has been modified through dredging and channelisation, regime equations are inappropriate tools to predict the potential for morphological adjustment, including bank erosion. Furthermore, analysis of stream power along the Thames (see Figure 5.1) suggests that in any case there is little potential for widespread morphological adjustment through erosion.

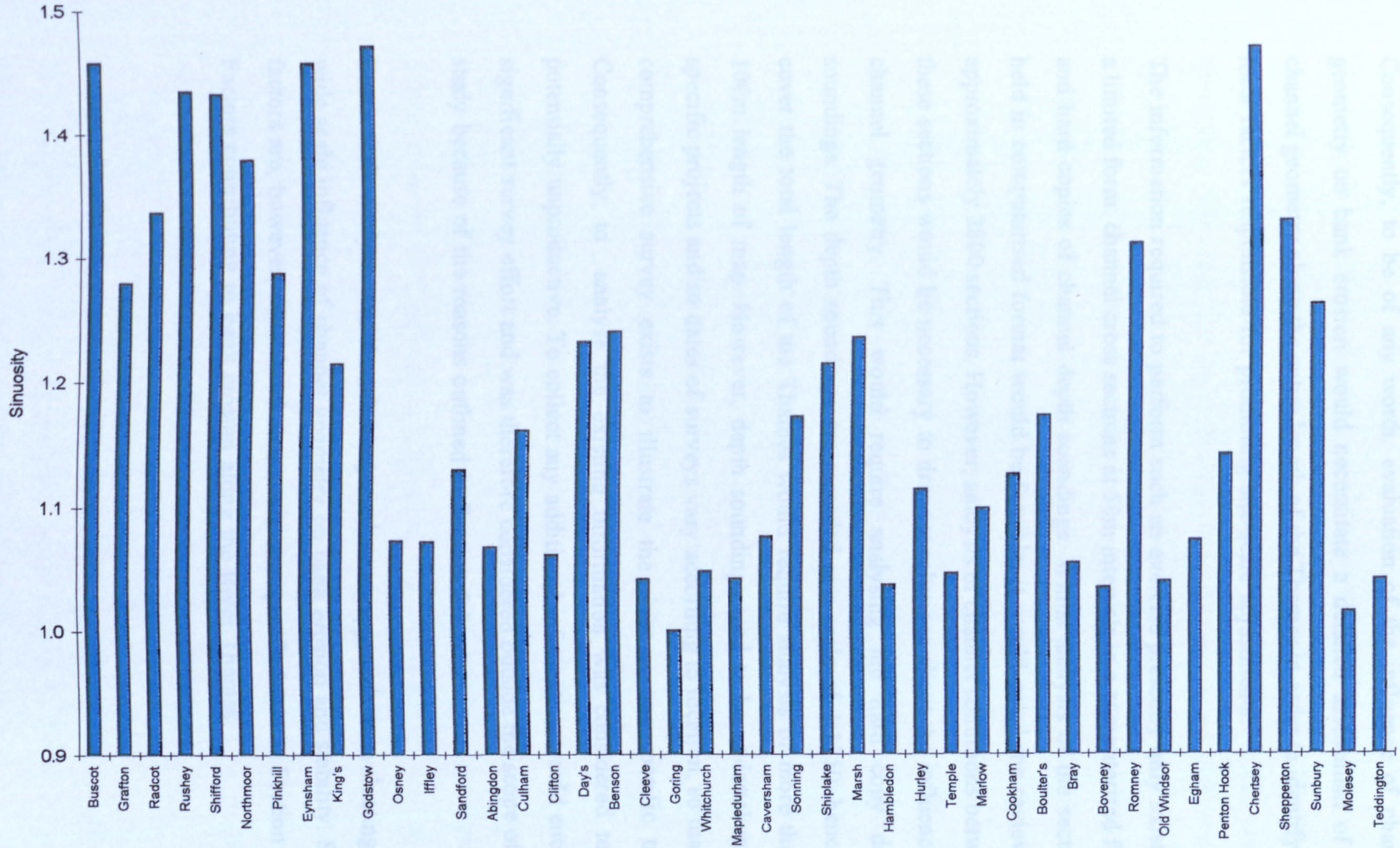


Figure 5.2 Channel sinuosity along each reach of the River Thames.

Consequently, to be of any worth, evaluation of the influence of channel geometry on bank erosion would necessitate a detailed assessment of the channel geometry along the entire length of the Thames in order to identify the local factors responsible for promoting site-scale adjustments.

The information required to perform such an exercise presently only exists in a limited form: channel cross sections at 50m intervals in a computerised form and hard copies of channel depth soundings. Whilst analysis of the sections held in computerised format would be feasible, it would entail the review of approximately 2800 sections. However, analysis of channel conditions between these sections would be necessary to draw conclusions about the influence of channel geometry. This would require analysing the hard copy depth soundings. The depth soundings are recorded at a scale of 1:1250, hence to cover the total length of the Thames would require analysis of more than a 100m length of map. However, depth soundings tend to be undertaken for specific projects and so dates of surveys vary according to location, so that no comprehensive survey exists to illustrate the river at one specific time. Consequently, to analyse the existing information was considered to be potentially unproductive. To collect any additional information would entail a significant survey effort and was therefore considered outside the scope of the study because of the reasons outlined in Section 5.1.

Reach scale analysis was therefore rejected as an approach to evaluating the wide scale influence of channel geometry on bank erosion and stability. Such factors are, however, considered on a more site specific basis in Section 5.6: Factors contributing to bank erosion along the River Thames.

5.4 River bank characteristics

Considerable insight into the processes and mechanisms of erosion, and the influences of bank morphology and vegetation, was gained during the compilation of The River Thames Bank Survey and the site-specific erosion monitoring. However, the River Thames Bank Survey allows only a broad analysis of the bank characteristics that influence erosion and stability, since a detailed morphological assessment of the banks was not undertaken. A simple bank morphology classification could have been devised that relates bank height and angle to bank stability, incorporating the theory of basal end point control, similar to that used by the US Army (1992). Such an assessment would have considerable value in determining the processes and mechanisms contributing to erosion. However, the nature of the survey technique meant that, in most instances, opportunities to observe bank morphology were limited, particularly due to the level of the water surface (which precluded easy inspection of the bank toe) and masking of the bank profile by thick bank vegetation (these and other limitations to the survey were discussed in Chapter Two: Approach and Methodology).

In the absence of detailed information regarding the morphology of the banks of the River Thames, the presence of bank vegetation and bank protection have been used as indicators of the susceptibility of the bank to erosion. Analysis of the influence of these bank characteristics on erosion has focused on two key aspects: first, the type and state of repair of hard bank protection; and second, where the banks are unprotected, the type of bank vegetation. The data presented in this Section are given in Appendix 5.2. Derivation of the data from the Thames River Bank Survey was discussed in Chapter Two: Approach and Methodology.

Figure 5.3 demonstrates the wide potential for bank protection to influence bank erosion along each reach, because almost a third of the banks of the Thames are protected in one form or another (see Appendix 5.2).

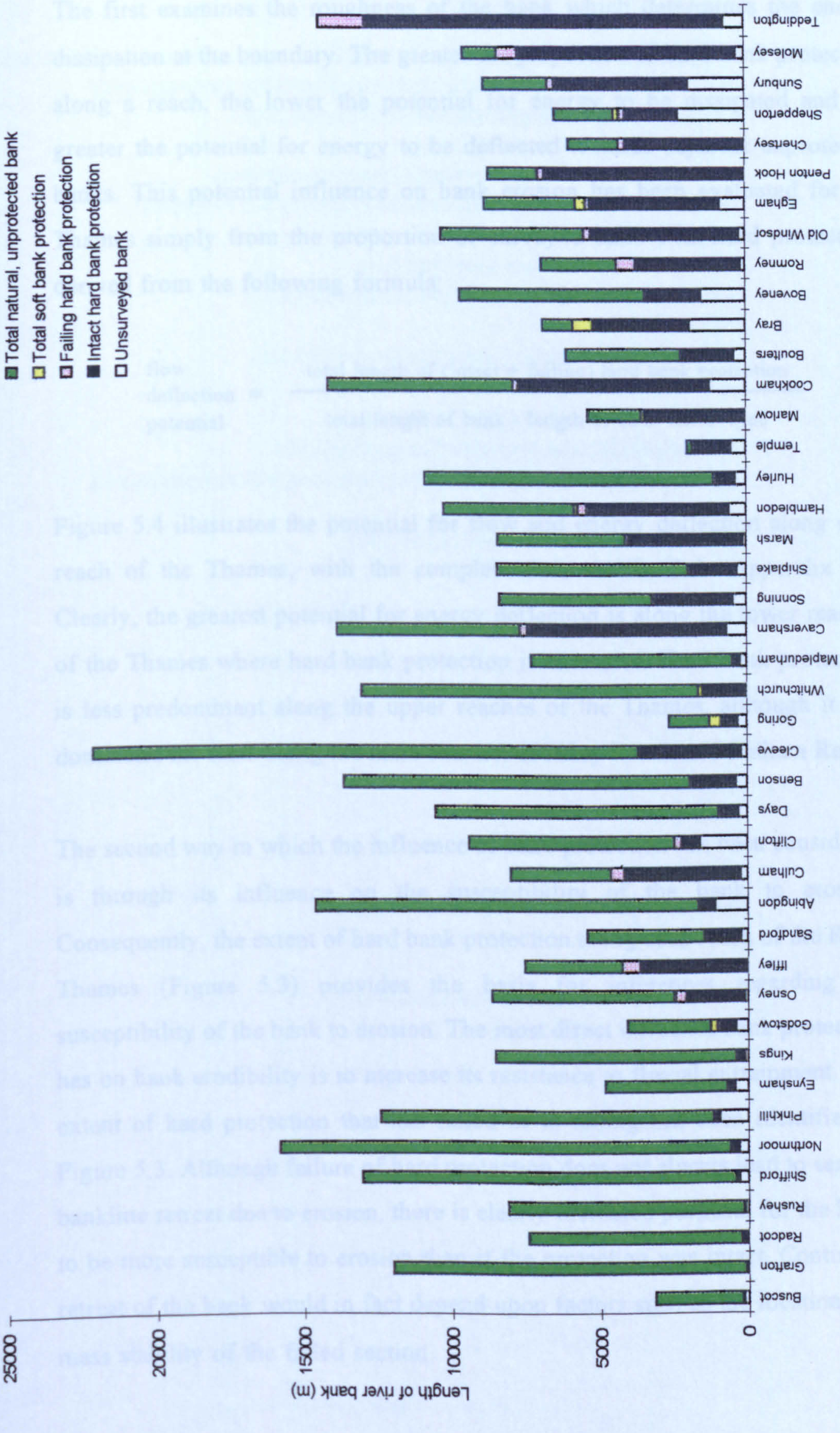


Figure 5.3 General character of the banks along each reach of the River Thames.

The influence of bank protection on erosion has been considered in two ways. The first examines the roughness of the bank which determines the energy dissipation at the boundary. The greater the proportion of hard bank protection along a reach, the lower the potential for energy to be dissipated and the greater the potential for energy to be deflected towards adjacent unprotected banks. This potential influence on bank erosion has been evaluated for the Thames simply from the proportion of surveyed bank with hard protection, derived from the following formula:

$$\text{flow deflection potential} = \frac{\text{total length of (intact + failing) hard bank protection}}{\text{total length of bank - length of bank unsurveyed}}$$

Figure 5.4 illustrates the potential for flow and energy deflection along each reach of the Thames, with the complete data set listed in Appendix 5.2. Clearly, the greatest potential for energy deflection is along the lower reaches of the Thames where hard bank protection is extensive. Hard bank protection is less predominant along the upper reaches of the Thames, although it still dominates the bank along the main channel of Iffley Reach and Culham Reach.

The second way in which the influence of bank protection has been considered is through its influence on the susceptibility of the bank to erosion. Consequently, the extent of hard bank protection along each reach of the River Thames (Figure 5.3) provides the basis for inferences regarding the susceptibility of the bank to erosion. The most direct influence bank protection has on bank erodibility is to increase its resistance to fluvial entrainment. The extent of hard protection that has failed or is failing has been identified in Figure 5.3. Although failure of hard protection does not always lead to serious bankline retreat due to erosion, there is clearly increased potential for the bank to be more susceptible to erosion than if the protection was intact. Continued retreat of the bank would in fact depend upon factors such as the location and mass stability of the failed section.

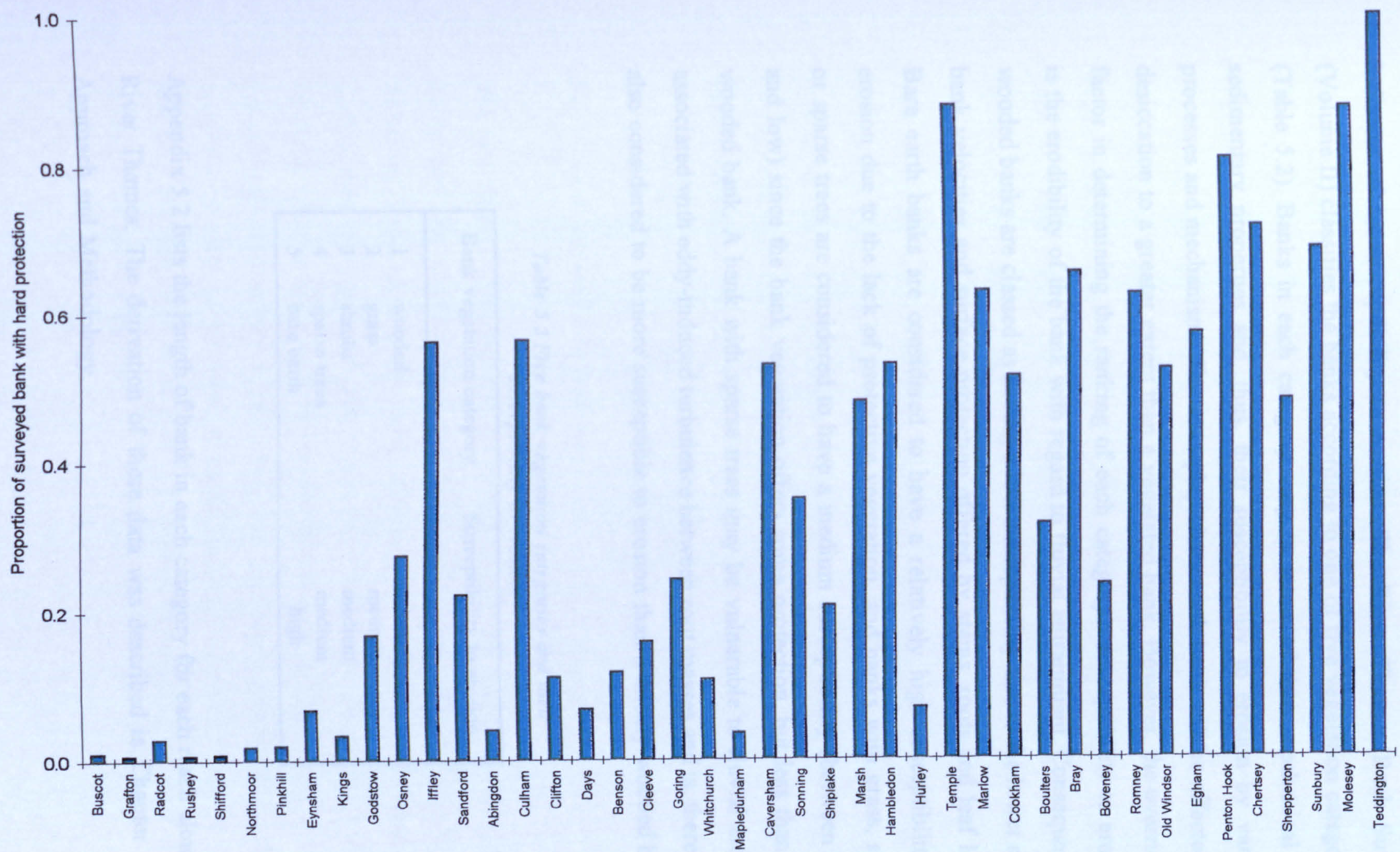


Figure 5.4 Flow deflection potential: proportion of surveyed bank with hard protection along each reach of the River Thames.

Where the bank is unprotected, the type of vegetation has been used as an indicator of its susceptibility to erosion. The River Thames Bank Survey (Volume II) classifies the banks according to one of five vegetation categories (Table 5.2). Banks in each category vary in terms of their mechanical and sedimentary properties and, thus, their susceptibility to erosion by various processes and mechanisms. For example, a bare earth bank will be affected by desiccation to a greater extent than a vegetated bank. However, the overriding factor in determining the ranking of each category's susceptibility to erosion is the erodibility of the bank with regard to fluvial entrainment. Consequently, wooded banks are classed as having a low susceptibility due to the lower near-bank velocities and surface protection offered by stems, roots and leaf litter. Bare earth banks are considered to have a relatively high susceptibility to erosion due to the lack of protective vegetation, and banks with grass, shrub or sparse trees are considered to have a medium susceptibility (between high and low) since the bank vegetation offers some protection, but less than at a wooded bank. A bank with sparse trees may be vulnerable to fluvial erosion associated with eddy-induced turbulence between root masses and is, therefore, also considered to be more susceptible to erosion than a thickly wooded bank.

Table 5.2 Five bank vegetation categories and their susceptibility to erosion.

Bank vegetation category		Susceptibility to erosion
1	wooded	low
2	grass	medium
3	shrubs	medium
4	sparse trees	medium
5	bare earth	high

Appendix 5.2 lists the length of bank in each category for each reach along the River Thames. The derivation of these data was described in Chapter Two: Approach and Methodology.

Combining the influence of hard bank protection with that of bank vegetation provides an indication of the overall erosion susceptibility of each reach of the River Thames (Figure 5.5).

It should be noted that this bank erosion susceptibility is only an indication of the bank's general ability to resist fluid shear stresses due to structural engineering or vegetation type. It cannot be assumed, for example, that grassed banks are always more susceptible to erosion than wooded banks since factors such as, bank profile geometry and the nature of the bank environment (potential for weakening and weathering) will also influence bank erodibility.

The length of bank with intact and failing soft bank protection has been included as a single category because, due to the complexity of "failure" in soft protection, general conclusions cannot be drawn regarding the impact on erosion susceptibility. In any case there is only a relatively short length of bank with soft protection.

5.5 Land, channel and bank use

The last chapter demonstrated the influence that the use of the channel, its banks and the adjacent land can have upon bank stability and erosion. Activities such as angling, boat mooring and walking can result in a deterioration of vegetation and mechanical damage to the bank. Similarly, livestock grazing and trampling (known collectively as 'poaching') and other agricultural practices such as ploughing, can also have a considerable influence upon the integrity of the bank. Most of these factors tend to operate locally and they are addressed in Section 5.6: Factors contributing to bank erosion along on the River Thames.

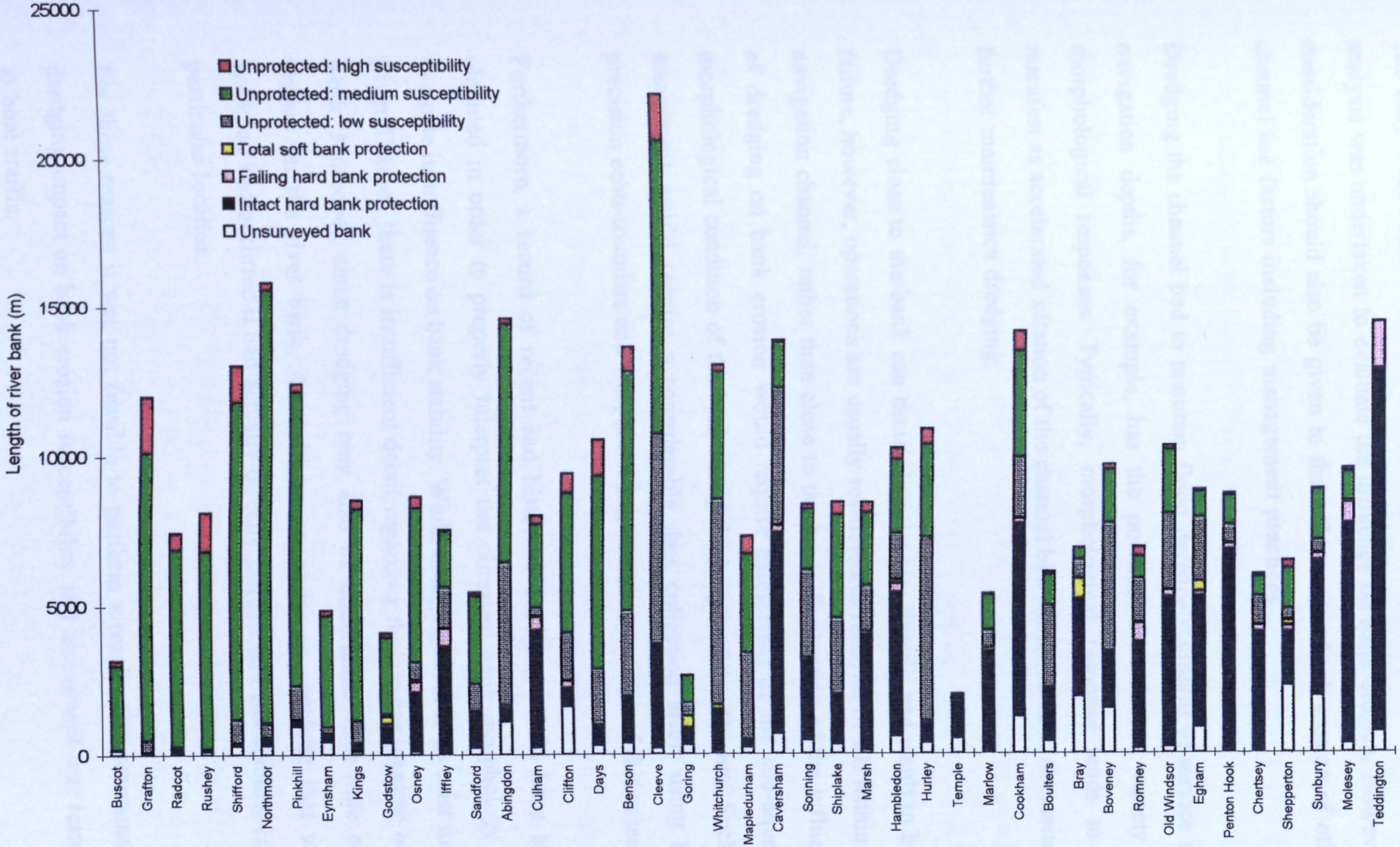


Figure 5.5 Bank vegetation and hard protection as indicators of bank erosion susceptibility along each reach of the River Thames.

The only wide scale channel use factor was boat traffic, and a reach scale analysis was undertaken to evaluate the influence on bank erosion. However, consideration should also be given to the influence on bank erosion of other channel use factors including management practices.

Dredging the channel bed to maintain flood defence standards of service and navigation depths, for example, has the potential to induce a variety of morphological responses. Typically, morphological response tends to be manifest as accelerated siltation of the channel bed which, in turn, necessitates further maintenance dredging.

Dredging close to the bank can destabilise the toe directly and result in bank failure, however, operations are usually restricted to removal of silt within the navigation channel, rather than close to the bank. Evaluation of the influence of dredging on bank erosion would require assessment of the sub-aqueous morphological condition of the bank along the length of the Thames. Such an assessment would require a considerable data collection effort using high precision echo-sounders and was, therefore, outside the scope of this research.

Furthermore, a record of recent and historical dredging would have to be obtained in order to properly interpret the observed bank morphology and evaluate its influence on bank stability. While dredging records do exist for the River Thames, there is insufficient detail regarding the precise location of the work. Moreover, since dredging may also be undertaken with little or no impact on the river bank, it would be erroneous to conclude that where dredging had occurred it had actually directly influenced bank stability in that particular location.

For these reasons it was not feasible to perform a reach scale assessment of dredging impact on bank erosion susceptibility and assessment was restricted to boat traffic.

Two aspects of boat traffic have been evaluated. The first aims to characterise wash generated by boats in terms of its potential to cause erosion. The second evaluates the potential for boat wash to impact the banks of the Thames on the basis of the number of craft passing through each lock and considering the width of the channel, since wash erosion tends to increase as the number of boats increases and the channel width decreases.

5.5.1 Characterisation of boat wash generated along the River Thames

The experimental approach adopted to monitor boat traffic and wash along the River Thames was detailed in Chapter Two: Approach and Methodology. Three sites were selected. Parameters recorded at each site included boat characteristics, boat velocities, bow wave heights and the maximum flow velocities generated near to the bank.

The sites were (1) adjacent to a wood piled bank, (2) a reeded bank, upstream of Wallingford Bridge, along Cleeve Reach, and (3) at a bank protected with Nicospan, upstream of Goring Lock. The Wallingford sites were located just upstream of the Upper Wallingford monitoring site, and the Goring site was located at the Goring bank profile monitoring site (see Appendix 5.3 for details of the locations of all sites).

The measurements taken at the wood piled, reeded and Nicospan protected banks are detailed in Appendix 5.3. The boat velocities, wave heights, maximum near-bank velocities and directions of passage recorded at each site are summarised in Table 5.3. These data were categorised according to Table 5.4 for frequency distribution analysis and are presented in this format in Appendix 5.3.

Table 5.3 Summary of boat traffic measurements taken at the wood piled, reeded and Nicospan protected banks during boat wash monitoring.

	Wood piled	Reeded	Nicospan
Monitoring time period, hours	7	2	3
Total number of boats	92	25	52
Average number of boats per hour	13	12	17
Boats travelling upstream, %	55	48	42
Boats travelling downstream, %	45	52	58
Mean boat velocity, km/hr (mph)	3.4 (2.1)	3.4 (2.1)	4.5 (2.8)
Minimum boat velocity, km/hr (mph)	0.8 (0.5)	1.8 (1.1)	2.6 (1.6)
Maximum boat velocity, km/hr (mph)	12.1 (7.5)	5.1(3.2)	6.0 (3.7)
Range in boat velocity, km/h (mph)	11.3 (7)	3.4 (2.1)	3.4 (2.1)
Most frequent category, km/hr (mph)	3.2 - 4.8 (2-3)	3.2 - 4.8 (2-3)	3.2 - 4.8 (2-3)
Boat velocities >3mph, %	5	4	37
Mean wave height, cm	9.6	3.6	9.0
Minimum wave height, cm	0.8	0.5	1.8
Maximum wave height, cm	39.0	13.0	18.5
Range in wave height, cm	38.2	12.5	16.7
Most frequent category, cm	5 - 10	0 - 5	5 - 10
Wave heights >15 cm, %	11	0	12
Mean Vmax, cm/s	2.8	6.5	6.0
Minimum Vmax, cm/s	2.1	2.7	2.6
Maximum Vmax, cm/s	8.9	17.9	10.1
Range in Vmax, cm/s	6.8	15.2	7.5
Most frequent category, cm/s	4 - 6	6 - 8	4 - 6
Vmax >8 cm/s, %	4	12	12

Note: Vmax = maximum velocity recorded 0.05m from the bank (cm/s).

Table 5.4 Categories for frequency distribution analysis of boat wash data.

Category	Boat velocity km/hr (mph)	Wave height cm	V max cm/s	Direction
1	0 - 1.6 (0-1)	0 - 5	2 - 4	Upstream
2	1.6 - 3.2 (1-2)	5 - 10	4 - 6	Downstream
3	3.2 - 4.8 (2-3)	10 - 15	6 - 8	
4	4.8 - 6.4 (3-4)	15 - 20	8 - 10	
5	>4	>20	>10	

Note: V max = Maximum near-bank velocity

The average numbers of craft passing the wood piled and reeded banks each hour were comparable; 13 and 12, respectively. However, the average number of craft passing the Nicospan protected bank at Goring each hour was 16, 30% greater than at the wood piled bank. Cleeve Reach, between Benson Lock and Cleeve Lock, is about 10.5km long (6.5 miles) compared to a length of approximately 1km between Cleeve Lock and Goring Lock. On the Goring Reach (Cleeve Lock to Goring Lock) there appeared to be an element of competitive 'jockeying for position' between boats as they attempted to get ahead of each other in the queue to enter the next lock. A reduction in boat traffic during lunch time was observed at the wood piled bank, which was the only site monitored at this time of day (Appendix 5.3).

For all three sites, boat velocities between 3.2km/hr and 4.8km/hr (2 - 3mph) were most frequent. However, only 5% and 4% of the boats passing the wood piled and reeded banks, respectively, were travelling at velocities greater than 4.8km/hr (3mph), compared to 37% of the boats passing the Nicospan protected bank at Goring.

The range in the mean boat velocities was small. At both the Wallingford sites the mean boat velocity was 3.4km/hr (2.1mph), compared to 4.5km/hr (2.8mph) at Goring. The minimum boat velocity recorded at each site during the monitoring period ranged by 1.8km/hr (1.1mph). The minimum at the wood piled bank was 0.8km/hr (0.5mph) which increased to 1.8km/hr (1.1mph) and 2.6km/hr (1.6mph) at the reeded and Nicospan protected bank, respectively.

There was a greater range in the maximum boat velocities. The highest velocity, 12km/hr (7.5mph), was measured at the wood piled bank upstream of Wallingford Bridge, for the craft pictured in Plate 5.1. In comparison, the maximum boat velocities recorded at the reeded and Nicospan banks were 5.1km/hr (3.2mph) and 6km/hr (3.7mph), respectively.

Plate 5.1
Speed boat travelling ~12km/hr (7.5mph) at the wood piled bank at Wallingford.

Frequency distributions of wave heights recorded adjacent to the wood piled bank, behind the reed bed at the reeded bank, and adjacent to the Nicospan protected bank are listed in Appendix 5.3 and summarised in Table 5.3. The most frequent wave heights recorded at the wood piled and Nicospan protected banks were between 5cm and 10cm, compared to heights of less than 5cm being the most frequent at the reeded bank. At the wood piled and Nicospan protected banks, respectively, 11% and 12% of the boats generated wave heights greater than 15cm, compared to none of the boats passing the reeded bank.

The mean wave heights recorded at the wood piled and Nicospan banks were 9.6cm and 9.0cm, again higher than the mean of 3.6cm at the reeded bank. There was little range in the minimum wave heights measured at the sites. The lowest minimum height, 0.5cm, was recorded at the reeded bank, the highest minimum, 1.8cm, at the Nicospan protected bank, and the minimum wave height recorded at the wood piled bank was 0.8cm. The lowest maximum wave height recorded at the banks, 13cm, was also at the reeded bank. The range in maximum wave heights recorded was greater than for the minimum wave heights, with maxima at the wood piled and Nicospan protected banks of 39cm and 18.5cm, respectively.

Frequency distributions of maximum near-bank velocities (Vmax) recorded at the wood piled, reeded and Nicospan banks are listed in Appendix 5.3 and summarised in Table 5.3. It should be noted that only 56 boats were included in the frequency distribution at the wood piled bank as equipment failure prohibited the measurement of Vmax during the first three hours of monitoring at this site (see Appendix 5.3).

The most frequent Vmax recorded at the wood piled and Nicospan protected banks was between 4cm/s and 6cm/s, compared to between 6cm/s and 8cm/s at the reeded bank. Only 4% of the boats passing the wood piled bank produced a Vmax greater than 8cm/s, compared to 12% of the boats passing both the reeded and Nicospan protected banks. The highest mean Vmax recorded, 6.5cm/s, was also at the reeded bank, compared to a mean at the Nicospan and wood piled banks of 6.0cm/s and 2.8cm/s, respectively. The range in minimum Vmax between the sites was only 0.6cm/s, with a minimum of 2.1cm/s at the wood piled bank, and 2.6cm/s and 2.7cm/s at the Nicospan and reeded banks, respectively. Similarly, the lowest maximum Vmax recorded at the sites was 8.9cm/s at the wood piled bank, compared to maximums of 10.1cm/s and 17.9cm/s at the Nicospan and reeded banks, respectively.

The frequency distributions of the directions of passage of craft at the wood piled, reeded and Nicospan protected banks are also given in Appendix 5.3 Table 5.3 shows the percentages of craft travelling upstream and downstream at each of the sites to be roughly comparable. At the reeded and the Nicospan protected banks, respectively, 52% and 58% percent of craft were travelling downstream, compared with 45% percent of the craft at the wood piled bank. There were no significant differences found between the positions and sizes of craft at each site.

Wave height and boat velocity:

The height at the bank of the diverging wave that propagates at an angle from the sides of the vessel, is the sum of the draw down and elevation in water surface at the bank. It is a function of the:

- hull design,
- displacement compared with the channel's cross section (blockage ratio),
- ratio of vessel to channel width,
- velocity and direction of vessel relative to the flow in the river,
- the location and alignment of navigation (sailing line) relative to the river alignment and geometry (PIANC, 1987; Bhowmik *et al.*, 1991).

The boat velocities recorded during the boat wash monitoring take no account of the velocity of flow within the channel. This could have had implications as almost 50% of the craft monitored were travelling downstream and could, consequently, have had higher velocities relative to the channel flow than the craft travelling upstream against the current. However, at all the Thames sites, the average flow velocities were observed to be less than 0.03m/s, constituting only 6% of the lowest boat velocity recorded. Consequently, the flow velocity within the channel was considered to have little effect on either the boat velocities or the velocities generated at the bank.

Figure 5.6 shows the relationship between the wave heights measured at the 3 bank sites and velocities of the passing boats. Two wave heights measured at the wood piled bank are not shown in Figure 5.6 since these heights, 26cm and 39cm, were generated by the only small speed boat observed during the monitoring period. This vessel passed the monitoring site twice, travelling at the highest recorded boat velocities. Plate 5.1 shows the wash generated by this craft when it was travelling at approximately 12km/hr (~7.5 mph). These wave heights were excluded from the regression analysis since the speed boat was not considered representative of boat traffic on the Thames. Alternatively, these 'uncharacteristic' wave heights are analysed independently from the remainder of the data (see Table 5.6).

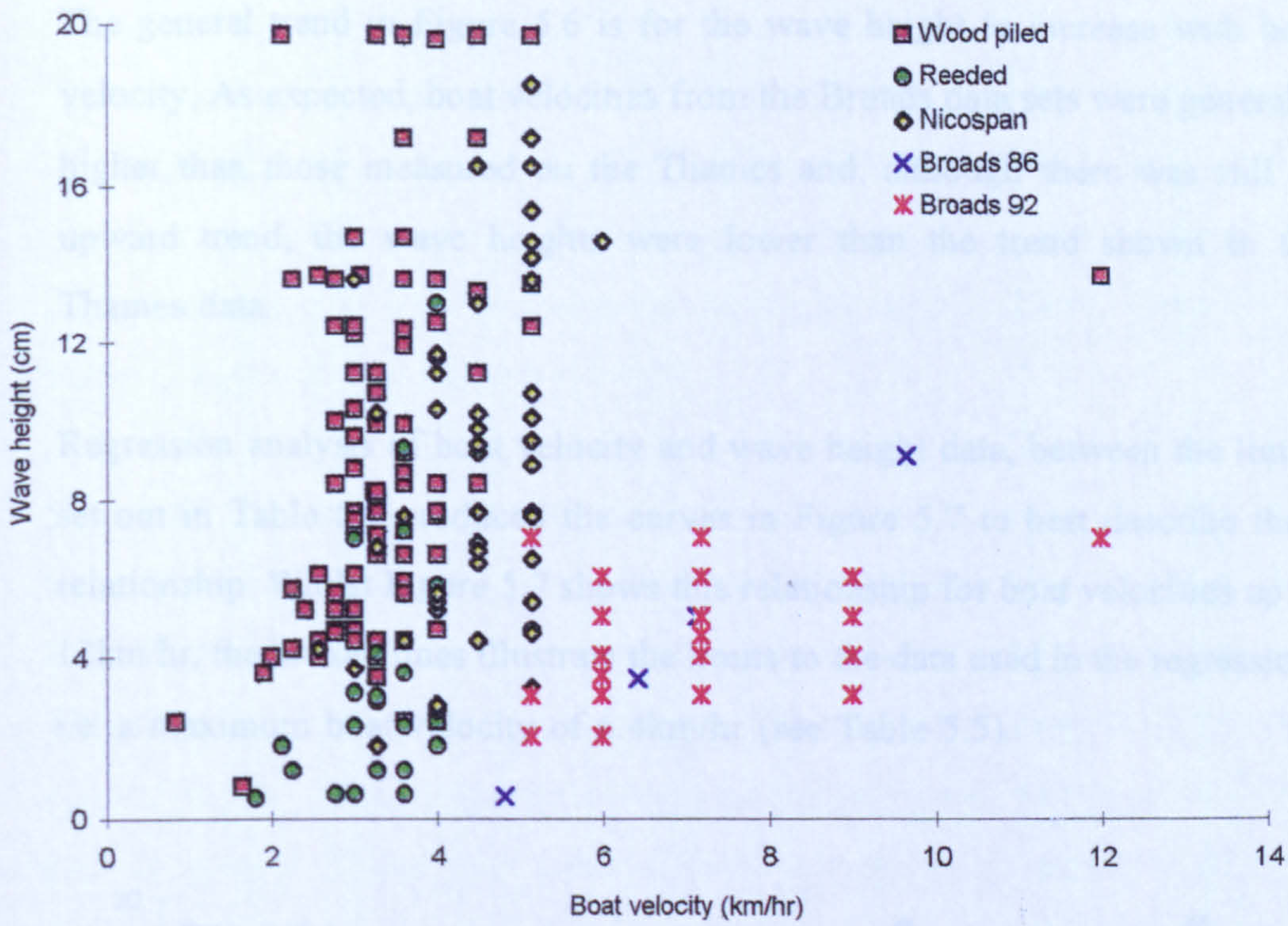


Figure 5.6 Boat velocity versus wave height for Thames and Broads data.

For comparison, data from two other boat wash monitoring studies, conducted on the Norfolk Broads, have been included in Figure 5.6. The Broads 1986 data was recorded at Salhouse Broad, off the River Bure, 2km downstream of Wroxham (Broads Authority, 1986), and the Broads 1992 data was recorded at a monitoring site at Brundall on the River Yare (Blake, 1993). The differences between the Thames and Broads data sets reflect the differences in channel, bank and vessel characteristics for the Thames and Broadland rivers and the influence on boat wash of channel depth, blockage ratio, vessel type and loading, and sailing line has been demonstrated by various researchers (WES, 1986; Bhowmik *et al.*, 1991; Bonham, 1980; Broads Authority, 1986). In addition, boats often travel faster on the Broadland rivers, where speed limits being as high as 11km/hr (7mph) on some stretches. There has recently been a speed limit of 8km/hr (~5mph) imposed along the Thames, although there has always been a requirement along the River Thames for boats to sail with an acceptably low wash and it has been "an offence to navigate...in a manner likely to...damage the banks of the Thames" (NRA, undated a, p.11).

The general trend in Figure 5.6 is for the wave height to increase with boat velocity. As expected, boat velocities from the Broads data sets were generally higher than those measured on the Thames and, although there was still an upward trend, the wave heights were lower than the trend shown in the Thames data.

Regression analysis of boat velocity and wave height data, between the limits set out in Table 5.5 produced the curves in Figure 5.7 to best describe their relationship. Whilst Figure 5.7 shows this relationship for boat velocities up to 12km/hr, the broken lines illustrate the limits to the data used in the regression, i.e. a maximum boat velocity of 6.4km/hr (see Table 5.5).

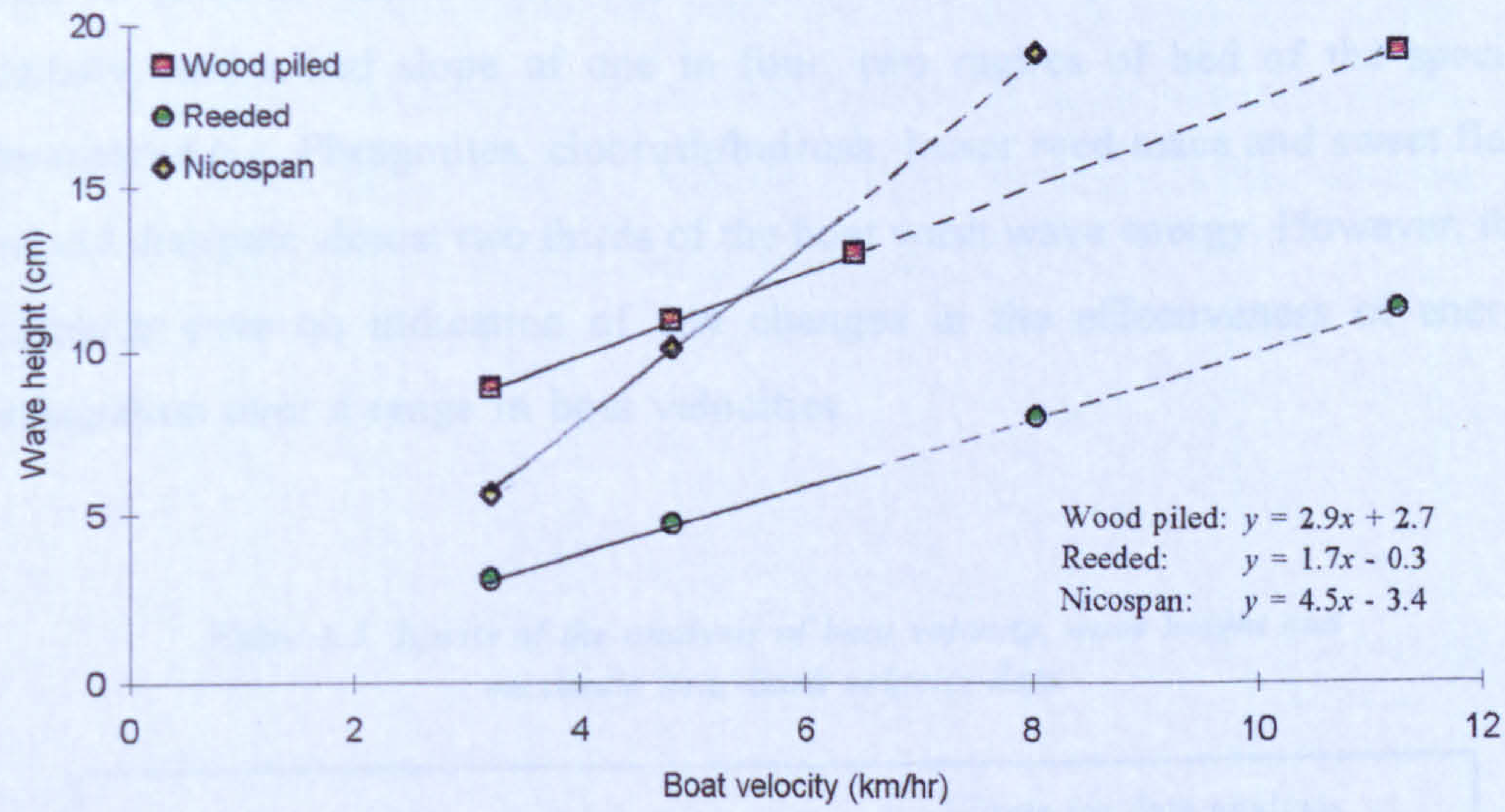


Figure 5.7 Best fit curve describing relationship between boat velocity and wave heights.

Figure 5.7 clearly shows that, for boat velocities up to ~6km/hr, the highest waves were generated at the wood piled bank, with intermediate wave heights at the Nicospan protected bank and the lowest waves at the reeded bank. At boat velocities greater than ~6km/hr, the regression analysis predicts higher wave heights at the Nicospan protected bank than at the sheet piled bank.

The regression lines shown in Figure 5.7 account for <10% of the variance in the data collected at the wood piled and reeded banks, and ~20% of that collected at the Nicospan protected banks. Consequently, output from the regression analysis only provides an indication of the likely relationship between boat velocity and wave height.

Figure 5.7 also suggests that the rate of increase in wave height with boat velocity was greatest at the Nicospan protected bank and lowest at the reeded bank. Interactions between boat wash and reed beds were monitored upstream of Wallingford Bridge by Bonham (1980). This research distinguished between the abilities of different species of reeds to dissipate wave energy at the bank, but, in general, found that under suitable conditions of depth, vegetation density, and a bed slope of one in four, two metres of bed of the species monitored (i.e. Phragmites, clubrush/bulrush, lesser reed mace and sweet flag) would dissipate almost two thirds of the boat wash wave energy. However, this research gave no indication of any changes in the effectiveness of energy dissipation over a range in boat velocities.

Table 5.5 Limits of the analysis of boat velocity, wave height and maximum near-bank velocity data.

	Limits for data analysis
Boat velocity (km/hr)	0 - 6.4
Boat velocity (mph)	0 - 4
Wave height (cm)	0 - 20
Maximum near-bank velocity (m/s)	0 - 0.12

Maximum near-bank velocity and wave height:

The velocities and fluid forces generated at the bank from the passage of craft are a function of the wave height, the characteristics of the bank and the near-bank flow geometry (PIANC, 1987). The relationships, at each of the banks, between the maximum velocities recorded at a distance of 0.05m from the bank (Vmax) and the heights of the boat-induced waves immediately adjacent to the bank are shown in Figure 5.8. The two highest recorded values of Vmax, 0.155m/s and 0.179m/s, were at the reeded bank and are not shown in Figure 5.8 or included in the regression analysis since they are considered to be uncharacteristic of the wash generated in this experiment. This is because the wash was generated from a small speed boat travelling up and down the river in a more reckless manner than the majority of boats that cruise the Thames. Instead, the velocities associated with these uncharacteristic waves are analysed independently from the bulk of the data to establish their potential to result in erosion of the bank material (see Table 5.6).

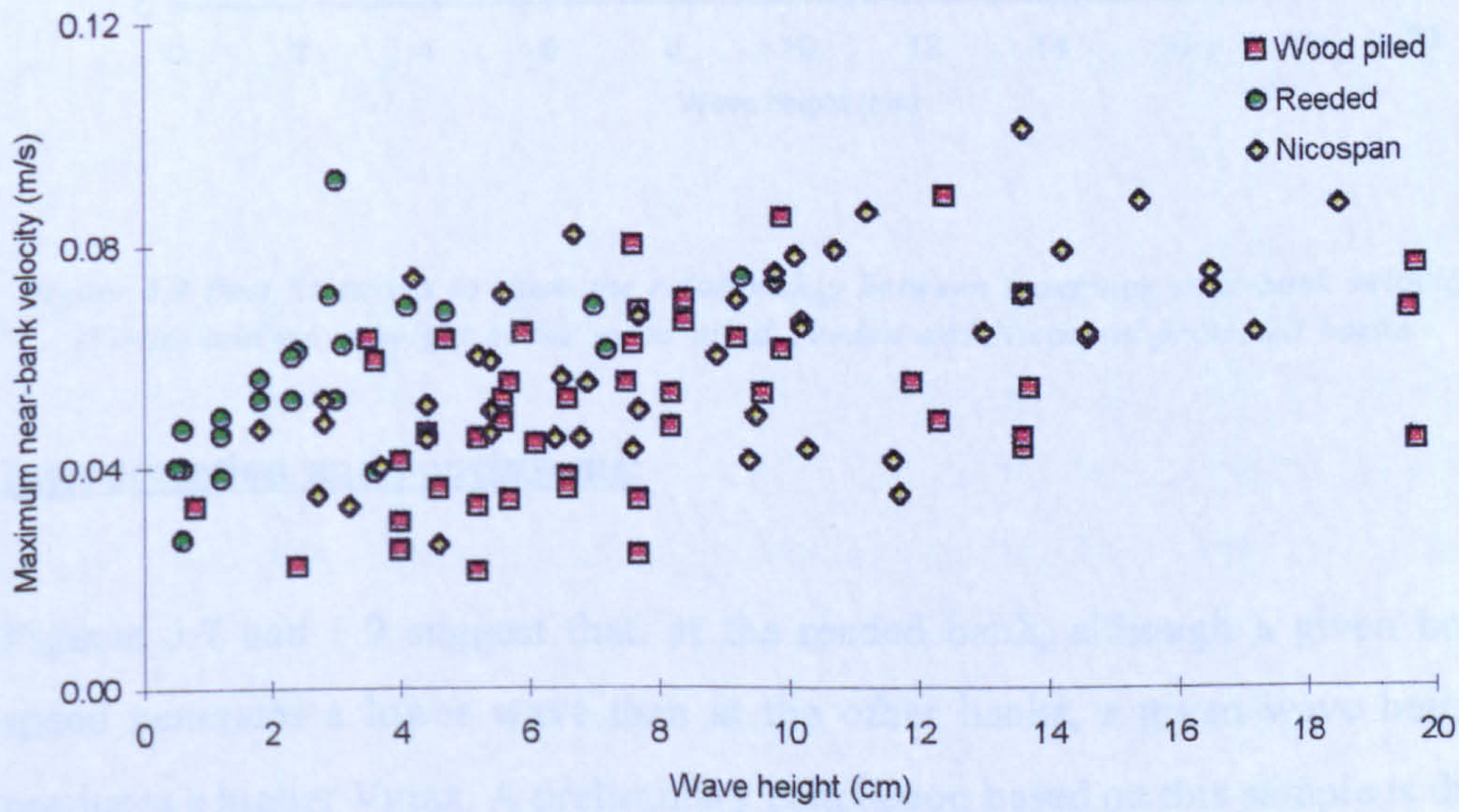


Figure 5.8 Maximum near-bank velocity (Vmax) versus wave height measured at the wood piled, reeded and Nicospan protected banks.

The trend for the remaining data in Figure 5.8 shows that Vmax increases with wave height. Best-fit regression lines are shown in Figure 5.9. These lines indicate that, for a given wave height, the maximum near-bank velocities produced at the reeded bank are higher than at the wood piled and Nicospan protected banks. Further, for a given wave height up to wave heights of about 10cm, the Vmax produced at the Nicospan protected bank is slightly higher than that at the wood piled bank. A reversal in this situation is seen for wave heights greater than 10cm. The best-fit line shown for the wood piled bank explains ~20% of the variance in the data, whilst almost 40% is explained by the regression lines shown for the reeded and Nicospan protected banks.

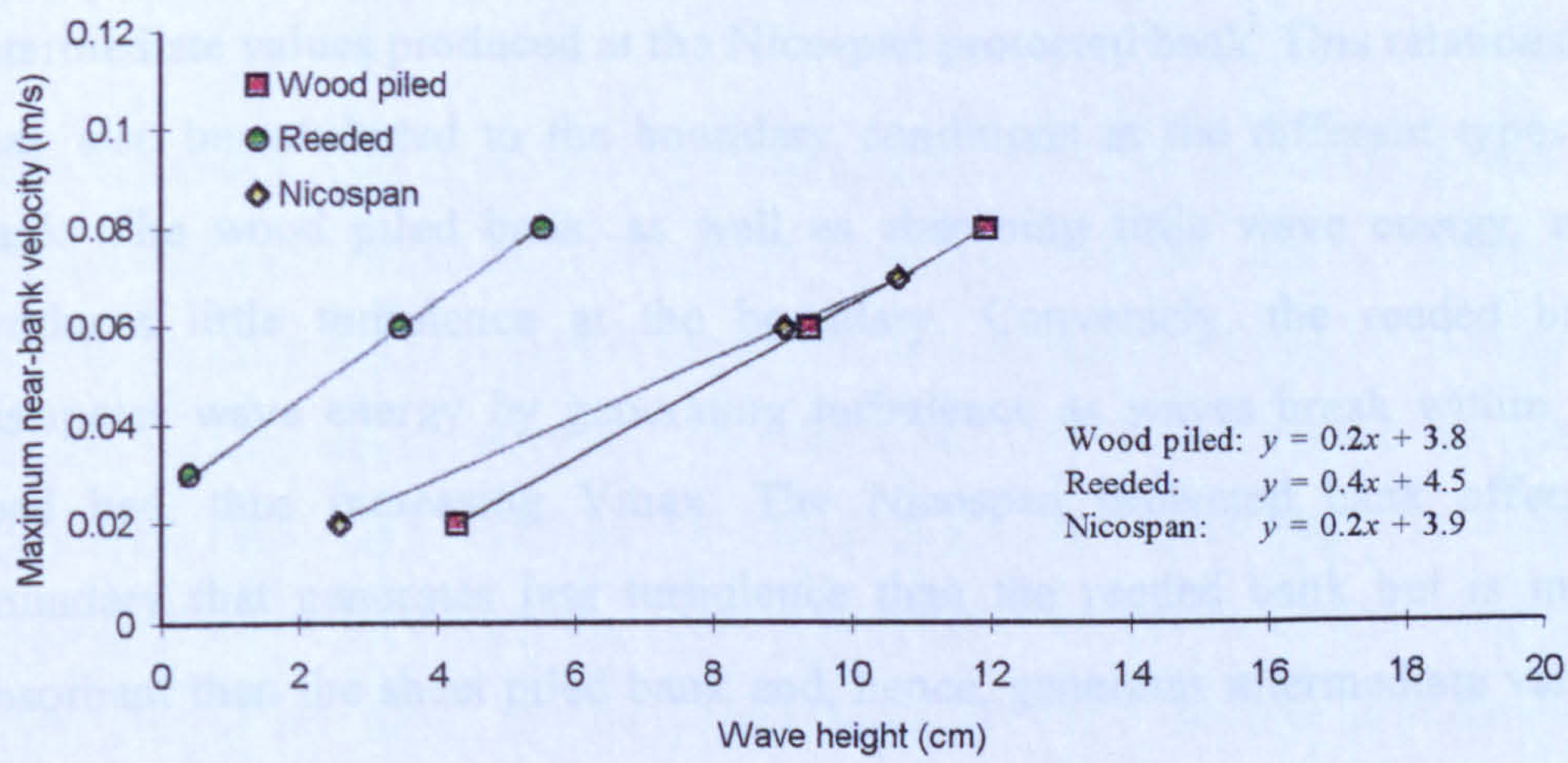


Figure 5.9 Best fit curves to show the relationship between maximum near-bank velocity (Vmax) and wave height at the wood piled, reeded and Nicospan protected banks.

Interpretation and conclusions:

Figures 5.7 and 5.9 suggest that, at the reeded bank, although a given boat speed generates a lower wave than at the other banks, a given wave height produces a higher Vmax. A preliminary conclusion based on this sample is that the influence of different bank environments on boat wash characteristics can be divided into two categories.

First, based on the relationship between boat velocity and wave height, the type of bank can influence the height of the wave generated at the bank. The wood piled bank presents a hard, vertical boundary where little or no wave energy is dissipated. The softer, geotextile of the Nicospan protected bank absorbs more wave energy, so that waves at this type of bank were lower than at the wood piled bank. Compared to the other two environments, the reeded bank has greater roughness and permeability and, therefore, dampens the energy of the approaching wash. Wave heights at the reeded bank are, consequently even lower than at the Nicospan protected bank.

The second influence, based on the relationship between wave height and near-bank velocity (Vmax), implies that waves at the hard, wood piled bank produce lower values of Vmax than the same waves at the reeded bank, with intermediate values produced at the Nicospan protected bank. This relationship may also be attributed to the boundary conditions at the different types of bank. The wood piled bank, as well as absorbing little wave energy, also produces little turbulence at the boundary. Conversely, the reeded bank dissipates wave energy by generating turbulence as waves break within the reed bed, thus increasing Vmax. The Nicospan protected bank offers a boundary that generates less turbulence than the reeded bank but is more absorbent than the sheet piled bank and, hence, generates intermediate values of Vmax.

Many additional factors influence boat wash and wave heights but were not accounted for in the monitoring study (Broads Authority, 1986; Garrad and Hey, 1988; Hemphill and Bramley, 1989). However, the results indicate that a reed fringe may be capable of significantly reducing the height, and thus the potential for bank erosion, from boat waves. Furthermore, the results demonstrate that hard wood piling absorbs little wave energy, supporting the use of the proportion of hard bank protection in a reach as an indicator of the potential for flow deflection (see Section 5.4 and Figure 5.4).

Bank shear stress:

Bank shear stress, τ_b, can be determined from a measurement of the near-bank velocity using the following relationship:

$$\tau_b = \rho(u.K)^2 / (\ln(z/z_o))^2$$

where, ρ = water density (1000kg/m^3), K = von Karman's constant (0.4), u = the measured water velocity (m/s) at height z (0.05m) above the boundary, and z_o is the effective roughness height (0.01m).

Maximum shear stresses at the wood piled, reeded and Nicospan protected banks during the boat wash monitoring are listed in Table 5.6. Shear stresses are included for both 'characteristic' boat and 'uncharacteristic' boat traffic.

The 'uncharacteristic' data include wave heights of 26cm and 39cm measured at the wood piled bank, and maximum near-bank velocities of 0.155m/s and 0.179m/s measured at the reeded bank. Due to equipment failure, no near-bank velocity was measured when the 39cm high wave was generated at the wood piled bank (see Appendix 5.3). The 26cm high wave generated a near-bank velocity of 0.048m/s, which was lower than would be expected when compared to the rest of the data. To gauge the potential shear stresses generated by 'uncharacteristic' boat traffic, a wave height of 39cm was selected to represent a 'worst case scenario' for wave generation. Using the relationship in Figure 5.9, a maximum near-bank velocity of 0.3m/s is derived for a wave height of 39cm. Similarly, to gauge the worst case scenario at the reeded bank, the near-bank velocity of 0.179m/s was used to calculate a shear stress of 1.98N/m^2 (see Table 5.6).

Measurements of maximum near-bank velocity were also recorded downstream of Wallingford Bridge during high flows experienced in September 1992, for comparison with the levels associated with 'characteristic' and 'uncharacteristic' boat wash impacts. A detailed account of the field technique is given in Chapter Two: Approach and Methodology, while the data recorded are presented in Appendix 5.3. At the time that these measurements were made the stage was approximately bankfull. In fact, the discharge was approximately $100m^3/s$ (as discussed in Chapter Four), whereas 'bankfull discharge' is estimated to be approximately $160m^3/s$ from the hydraulic model referred to in Section 5.2 (Thames Water, 1988b). A peak velocity of 0.164m/s was observed producing a calculated bank shear stress of 1.66 N/m^2.

Table 5.6 summarises the measured near-bank velocities and calculated bank shear stresses in the vicinity of Wallingford Bridge and Goring Lock, i.e.

- the 'characteristic' boat traffic at the wood piled, reeded and Nicospan protected banks;
- the 'uncharacteristic' boat traffic at the wood piled and reeded banks;
- the high flows experienced at Wallingford in September 1992.

Table 5.6 Summary of bank shear stresses generated at Wallingford and Goring.

	Near-bank velocity (m/s)	Bank shear stress (N/m^2)
Boat wash monitoring at wood piled, reeded and Nicospan protected banks:		
Characteristic boat wash:		
Wood piled[1]	0.098	0.49
Reeded[1]	0.092	0.52
Nicospan[2]	0.101	0.63
Uncharacteristic boat wash:		
Wood piled[1]	0.30	5.56
Reeded[1]	0.179	1.98
High flows on 29 September 1992:		
Mean[3]	0.103	0.66
Maximum[3]	0.164	1.66

Notes: see Appendix 5.3 for locations of sites:
[1] Cleeve Reach: upstream of Wallingford Bridge;
[2] Goring Reach: upstream of Goring Lock;
[3] Cleeve Reach: downstream of Wallingford Bridge;

The results listed in Table 5.6 suggest that the high discharge experienced in September 1992 was, potentially, more erosive than the wash generated from the 'characteristic' boat traffic. However, the shear stresses generated by the 'uncharacteristic' boat traffic were higher than those generated by the high flows in September 1992. It should be noted that the shear stress calculated from the wave height of 39cm (that is, the near-bank velocity = 0.3m/s) relies on the relationship between wave height and near-bank velocity shown in Figure 5.9. Since this relationship was derived from data with wave heights of less than 20cm, it is possible that the near-bank velocity is overestimated. Nonetheless, since the near-bank velocity measured at the reeded bank generated a shear stress of 1.98N/m^2, it would be reasonable to assume that the 'uncharacteristic' wash generated at the wood piled bank could result in shear stresses of the order of at least 2N/m^2, and certainly higher than the peak shear stress measured during the high flows in September 1992.

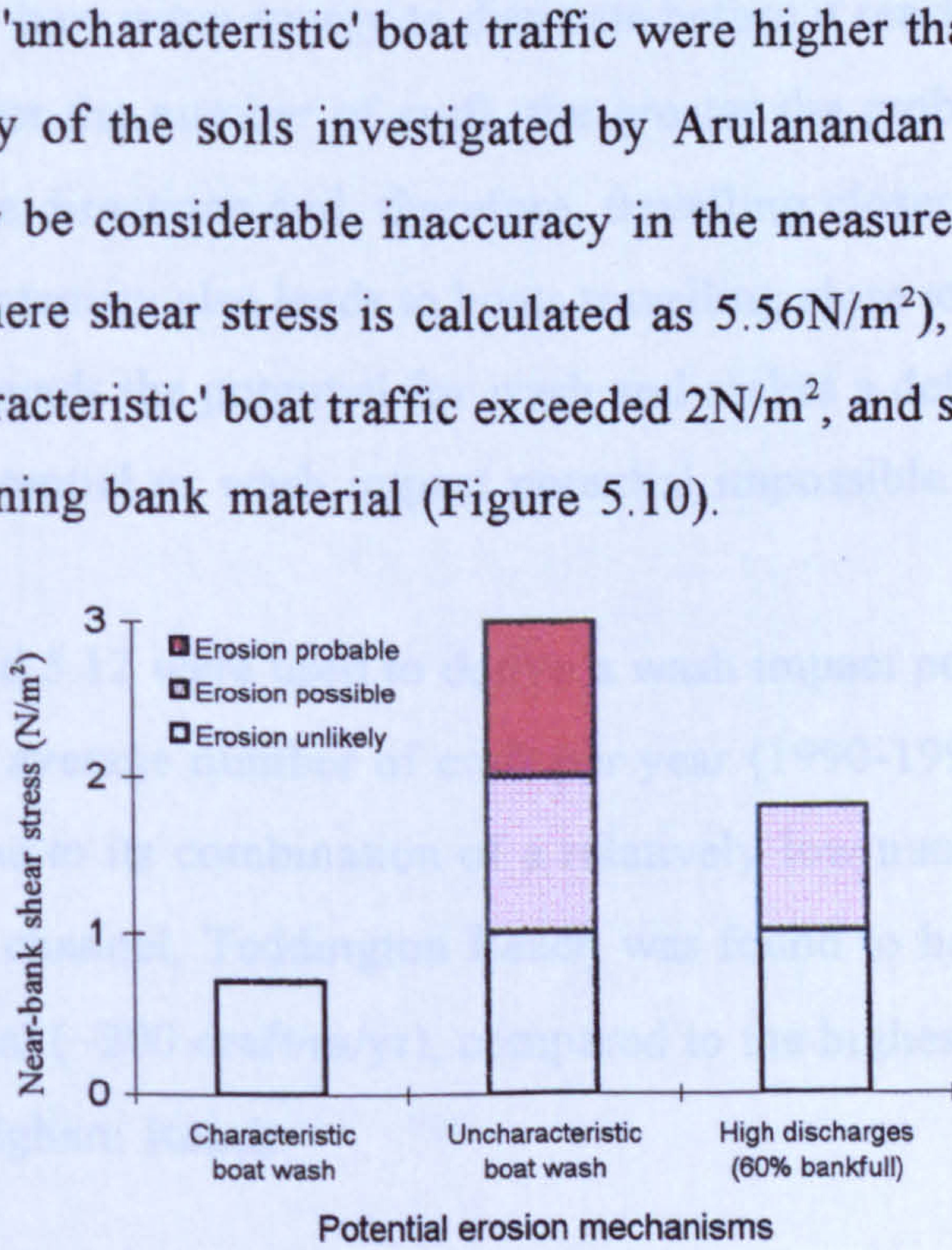
When predicting the erosion effectiveness of a flow event, timing may be just as important as magnitude and duration. The influence of factors that prepare the river bank for erosion, such as frost action, wetting and drying cycles and mechanical damage, should not be underestimated. Factors contributing to erodibility of the river bank vary temporally as well as spatially, as do the mechanisms of erosion. During the boating season, water surface levels are consistently low, and mechanical damage from public access, livestock and mooring can weaken bank material to the extent that waves are capable of removing loosened particles. Boat waves repeatedly breaking at the low summer water levels not only weaken the bank material and make it more erodible, but also erode notches that undercut the bank. Furthermore, the duration of the boating season is considerably longer than that of high flows events encountered along the Thames. Consequently, it remains a difficult task to evaluate the absolute and relative contributions of high flows and boat wash to the overall erosion.

No fluvial entrainment was observed during the boat wash experiment and the shear stresses generated by the 'characteristic' boat traffic generally fall below the critical shear stresses for similar soils investigated by Arulanandan *et al.* (1980). It would, therefore, be reasonable to conclude that the 'characteristic' boat traffic was unlikely to result in entrainment of intact bank material.

Similarly, no significant bank erosion was actually observed during the high flows in September 1992, although it was noticeable that the bank surface was smoothed as a result of fluvial entrainment of soil crumbs weakened by summer desiccation. Some bank failures did occur following hydrograph recession, but this was attributed to drawdown effects rather than fluvial entrainment. The average shear stress measured during the high flows of September, 1992 (0.66N/m^2) was generally below the critical shear stresses for similar soils (Arulanandan *et al.*, 1980). Similarly, the peak shear stress (1.66N/m^2) was below the critical shear stress of many of the soils investigated. Whilst these stresses would probably be insufficient to cause significant erosion of intact materials, they might well be adequate to entrain loosened soil particles.

Shear stresses generated by 'uncharacteristic' boat traffic were higher than the critical shear stress of many of the soils investigated by Arulanandan *et al.* (1980). Although there may be considerable inaccuracy in the measurements at the wood piled bank (where shear stress is calculated as 5.56N/m^2), shear stresses generated by 'uncharacteristic' boat traffic exceeded 2N/m^2, and should have been capable of entraining bank material (Figure 5.10).

Figure 5.10
A comparison of the potential for erosion resulting from 'characteristic' and 'uncharacteristic' boat traffic and the high flow discharges in September 1992



5.5.2 The impact of boat wash along the River Thames

Boat traffic along the Thames has decreased since its peak in the mid-1970s (NRA, 1994b), although use of the river has started to increase again recently (Environment Agency, 1998i). The potential for the banks to be impacted by boat wash is considered here as a function of boat traffic and channel width (see Chapter Two: Approach and Methodology). It is recognised that, in practice, the relationship is actually more complicated and some of the many aspects influencing the relationship have been discussed above. However, it is argued that the major factors remain traffic and channel width and, on this basis, the assessment provides a simple approach through which to evaluate the relative potential impact of boat wash on the banks of each reach.

Data on the average number of craft per year passing through each lock for the period 1990 to 1996 have been plotted (Figure 5.11). Traffic intensities vary by up to a factor of five, indicating that the potential for boat wash generation is not uniformly distributed along the river. The average channel width for each reach is shown in Figure 5.12 and has been used here to evaluate the potential for boat wash to impact the bank. Along the wider, lower reaches, there is greater potential for bow wave energy to dissipate before it reaches the bank. Conversely, the greater the number of craft, the greater the probability of boats passing in opposite directions and, therefore, travelling closer to the bank. Similarly, high boat intensity also leads to boats travelling close together in line astern, which compounds the potential for wash and makes a definitive evaluation of boat wash potential or wash impact potential impossible.

The data in Figures 5.11 and 5.12 were used to derive a wash impact potential (Figure 5.13), which is the average number of craft per year (1990-1996) per metre width of channel. Due to its combination of a relatively low number of craft and a relatively wide channel, Teddington Reach was found to have the lowest wash impact potential (~200 craft/m/yr), compared to the highest value (~520 craft/m/yr) for the Egham Reach.

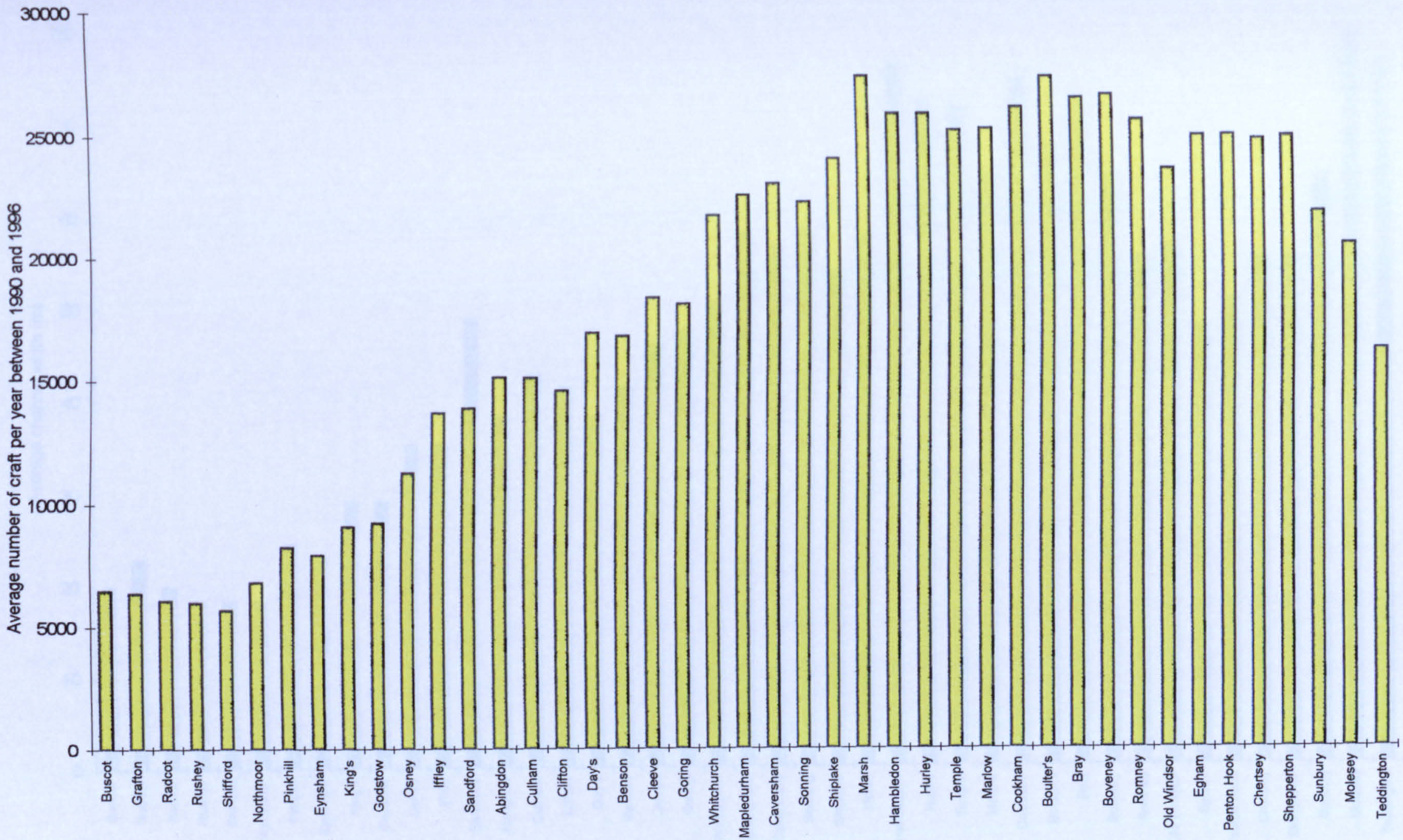


Figure 5.11 Boat traffic along each reach of the River Thames: annual average between 1990 and 1996.

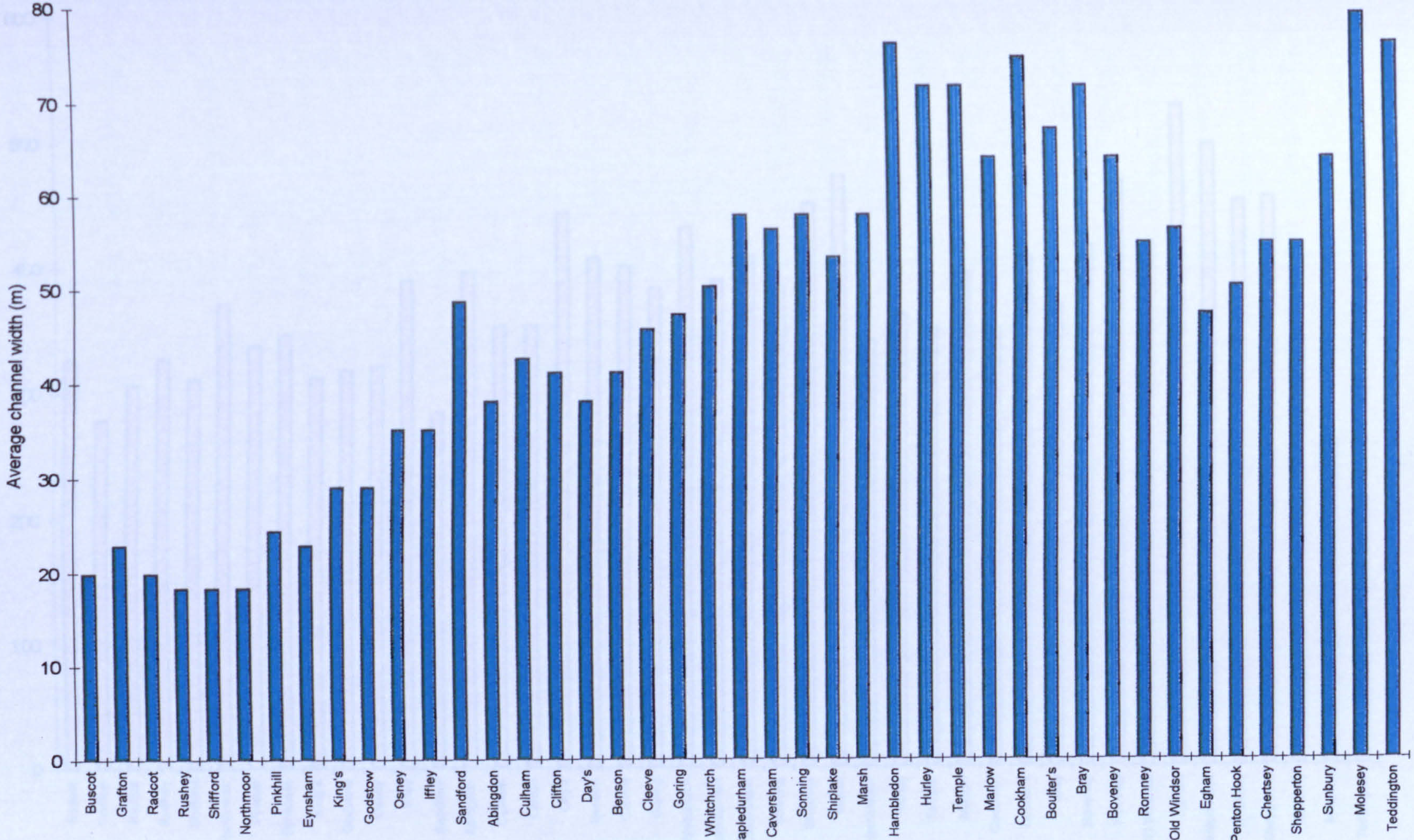


Figure 5.12 Average channel width along each reach of the River Thames.

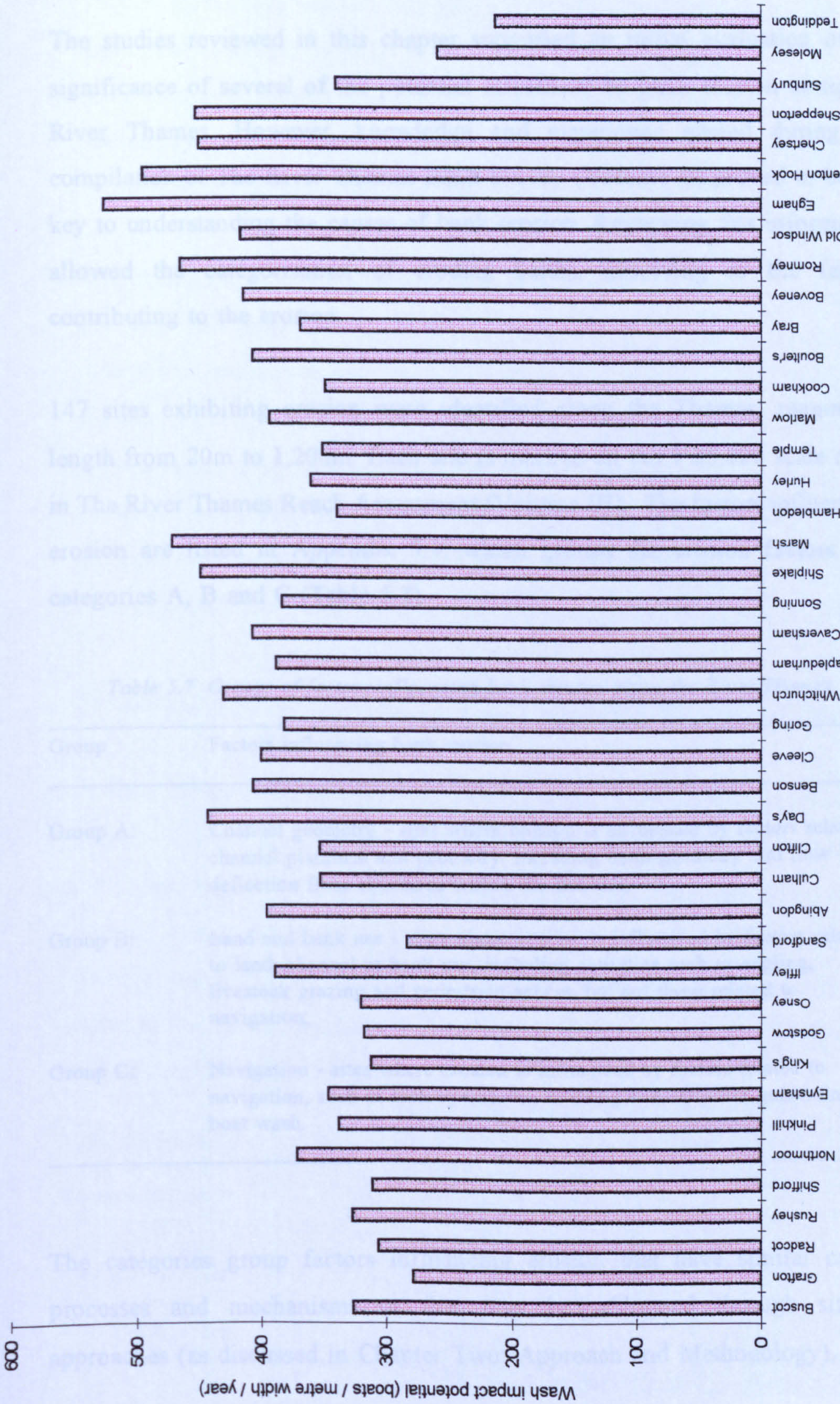


Figure 5.13 Wash impact potential along each reach of the River Thames.

5.6 Factors contributing to bank erosion along the River Thames

The studies reviewed in this chapter supported an initial evaluation of the significance of several of the potential influences on bank erosion along the River Thames. However, knowledge and experience gained during the compilation of The River Thames Bank Survey (Volume II) proved to be the key to understanding the causes of bank erosion. Reviewing this information allowed the categorisation of eroding banks, according to the factors contributing to the erosion.

147 sites exhibiting erosion were identified along the Thames, ranging in length from 20m to 1,200m. Each site is marked on the 1:25,000 scale maps in The River Thames Reach Assessment (Volume III). The factors influencing erosion are listed in Appendix 5.4, which groups the erosion factors into categories A, B and C (Table 5.7).

Table 5.7 Groups of factors influencing bank erosion along the River Thames

Group	Factors influencing bank erosion
Group A:	Channel geometry - sites where erosion is influenced by factors related to channel planform and geometry, including bank geometry and flow deflection from structures within the channel;
Group B:	Land and bank use - sites where erosion is influenced by factors related to land, channel or bank use, including activities such as angling, livestock grazing and pedestrian access, but not those related to navigation;
Group C:	Navigation - sites where erosion is influenced by factors related to navigation, such as lock operations, mooring and activities generating boat wash.

The categories group factors influencing erosion that have similar causal processes and mechanisms or that may be addressed through similar approaches (as discussed in Chapter Two: Approach and Methodology).

Although this is a broad classification, it is practical in that all of the dominant factors influencing erosion fall into one of the groups. This partially results from the regulated regime of the River Thames. Some factors, such as temperature, wetting/drying cycles and freeze-thaw action, do not feature in a specific group but are considered implicitly, through the bank's susceptibility to erosion (see above analysis of bank morphology and vegetation).

The information collected for the 147 erosion sites and included in Appendix 5.4 was less extensive than that demanded by published bank erosion assessment methodologies (eg. US Army, 1992; NRA, 1996; Environment Agency, 1997) because on the regulated River Thames determination of the factors influencing erosion was relatively straight forward. It made use of evidence readily available from characteristic indicators of causal processes and mechanisms. These indicators were similar at all sites, and so only selected examples are given below to demonstrate some the different factors identified.

<u>The influence of factors from Group A - Channel planform and geometry:</u>

Perhaps the most easily identifiable factor within this group is erosion along the outer bank at meander bends. Such erosion tends to be most obvious along the upper reaches of the Thames, where the banks are unprotected and the channel is relatively sinuous. For example, Plate 5.2 shows the reach of river downstream of Buscot Lock, where sinuosity was identified as a contributory factor to the erosion (see The River Thames Reach Assessment (Volume III) and Appendix 5.4).

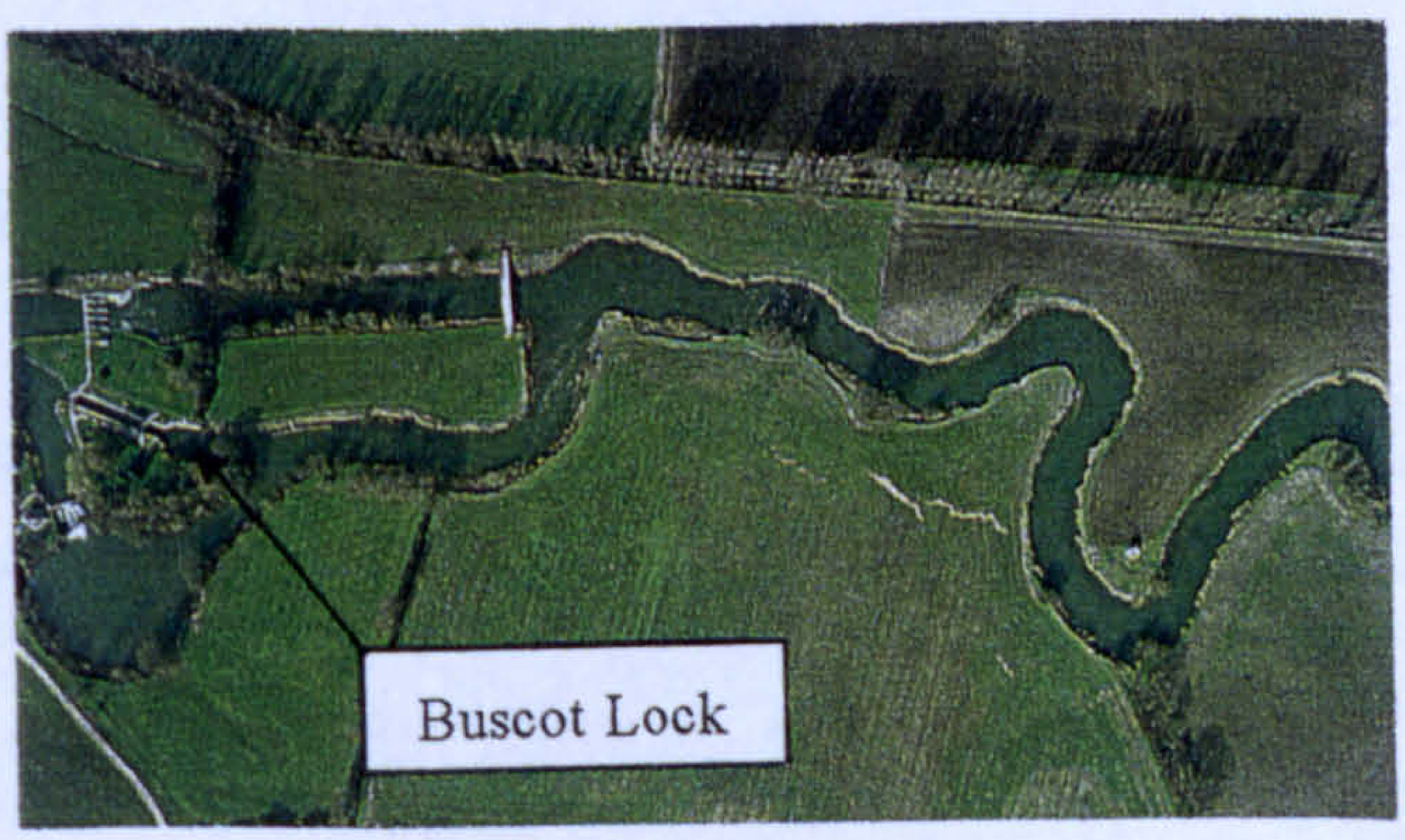


Plate 5.2 Sinuosity along the Upper Thames, including erosion downstream of Buscot Lock (see Bank erosion sites 5 and 6, Map 2, Volume III) (Courtesy of Environment Agency)

Changes in the alignment of the channel can cause flow to impinge against the bank, resulting in erosion. For example, at Marlow the current from behind Scout Island enters the main channel obliquely, causing the flow to impinge upon the opposite bank (Plate 5.3). This resulted in erosion and the formation of a steep river cliff. Since completion of The River Thames Bank Survey, this site has been protected with steel sheet piling (see Chapter Six) and it has, therefore, been removed from the sites identified as eroding (although The River Thames Bank Survey has not been updated).

Plate 5.3 Installation of sheet piling to protect the eroding cliff face at Marlow (see also Erosion control case study no. 15: Plate 6.15, Map 31, Volume III)

Other examples of impinging flow may be found downstream of weirs, including, for example, the bank opposite Caversham Weir (Plate 5.4). Although others factors, such as pedestrian access and boat wash also influence the bank here, impinging flow from the weir clearly contributes significantly to erosion.

Plate 5.4 Erosion opposite Caversham Weir (see Bank erosion site no. 83, Map 24, Volume III). Aerial photograph courtesy of Environment Agency.

Similarly, turbulence generated downstream of bridges may result in bank erosion. For example, this phenomenon was observed at the Lower Wallingford monitoring site discussed in Chapter Four (see Plate 5.5). Although other influences on the bank were identified, including pedestrian trampling and drawdown, erosion due to turbulence from the bridge also contributes to bank retreat.

Plate 5.5 Bank erosion downstream of Wallingford Bridge.

Bridges can induce bank erosion indirectly through their tendency to induce sedimentation, or shoaling, where the flow expands downstream of the channel constriction at the structure. Depending on the mobility of the sediments in shoal, deposition of a medial bar can result in bank erosion as the width adjusts to compensate for shoal formation. However, this indirect effect is not present along the Thames because shoals would compromise the navigation of the Thames and are, therefore, removed.

The influence of factors from Group B - Land and bank use:

The factors influencing erosion within this group include grazing, angling and pedestrian access. The influence of stock poaching (grazing and trampling) is evident at several sites along the upper reaches of the Thames, where land use is predominantly agricultural. For example, downstream of Eynsham Lock cattle trampling is the predominant cause of bank retreat (Plate 5.6).

Plate 5.6 Poaching of the river bank downstream of Eynsham Lock (see Bank erosion site no. 36, Map 9, Volume III).

Where livestock repeatedly access the water's edge, mechanical damage and compaction of the bank often prevents vegetation colonisation. For example, Plate 5.7 shows erosion at a cattle watering point near Bablock Hythe, in the Pinkhill Reach.

Plate 5.7 Cattle access point near Bablock Hythe along Pinkhill Reach (see Bank erosion site no. 32, Map 7, Volume III).

Similarly, pedestrian access can lead to trampling and compaction, damaging the bank material, destroying vegetation and preventing it from colonising. These impacts can be identified along the towpath upstream of Wallingford Bridge prior to bank protection work (Plate 5.8). This site corresponds to the Upper Wallingford erosion monitoring site (Chapter Four).

Plate 5.8 Erosion of the surface of the tow path due to pedestrian access, upstream of Wallingford Bridge.

Considerable mechanical damage can also result from public access for recreation. For example, anglers frequently cut back vegetation and may purposely dig into the bank to facilitate access to the channel. Plate 5.9 shows a short length of bank along the Old Windsor Reach where concrete bagwork has been displaced at an angling 'swim'. Riparian and aquatic vegetation at each swim has been cut back and the bank protection has been displaced, creating the opportunity for fluvial erosion. In contrast the bagwork has remained intact between the swims. Although other factors will usually be involved, for example channel geometry, public access remains a primary cause of many site-specific erosion problems.

Plate 5.9 Displacement of concrete bagwork at angling swim along Old Windsor Reach (see Bank erosion site no. 127, Map 36, Volume III).

The influence of factors from Group C - Navigation:

A range of navigation related activities may lead to bank erosion. For example, mechanical damage to the bank may result from the use of mooring pegs, as shown in Plate 5.10, taken at Deadwater Ait, in the Romney Reach.

Plate 5.10 Damage of the river bank resulting from the use of mooring pegs at Deadwater Ait, Romney Reach (see Bank erosion site no. 124, Map 35, Volume III)

Manoeuvring close to the bank may result in erosion from the propeller jet and/or mechanical damage by the hull if the vessel actually strikes the bank, for example when mooring. Sites regularly used for mooring often have steep banks and may display evidence of soil surface shearing due to scraping by boat hulls, as shown at the Brocas (Plate 5.11).

Plate 5.11 Shearing of the vertical cliff face at the Brocas along Romney Reach (see Bank erosion site no. 125, Map 35, Volume III)

Whilst problems are often centred on mooring sites, navigation-related erosion due to boat wash characteristically produces bank retreat along the inside of meander bends where wave energy tends to be concentrated, as observed upstream of Swinford Bridge (Plate 5.12). This allows navigation-related erosion to be differentiated from fluvial erosion, which is usually concentrated along the outer bank at bends.

Plate 5.12 Erosion along the inside of a meander bend, upstream of Swinford Bridge, Eynsham Reach (see Bank erosion site no. 34, Map 8, Volume III)

Analysis of factors contributing to erosion along the River Thames

To support spatial analysis of the distribution of factors contributing to bank erosion along the Thames, the 147 erosion sites were allocated to reaches and categorised according to the factors contributing to erosion.

Erosion at many of the sites was observed to be influenced by common combinations of factors from Groups A, B and C. Combining the factors to explain observed suites of factors produced 7 compound categories that encompassed the possible combinations of groups of factors contributing to erosion at any particular site (Table 5.8).

Figure 5.14 shows the extent of erosion identified along each reach of the River Thames. The base data and percentage values are listed in Appendix 5.4. The results show that approximately 10% of the banks of the Thames were identified as eroding, although this does not necessarily mean that the erosion identified constitutes an erosion problem, nor does it mean that erosion is limited exclusively to these sites (see limitations discussed in Chapter Two).

Table 5.8 Seven categories of factors contributing to bank erosion along the River Thames.

Category	Groups of factors influencing erosion
Category A:	erosion influenced only by factors in Group A, i.e. channel planform and geometry, including bank geometry and deflection from structures within the channel
Category B:	erosion influenced only by factors in Group B, i.e. land or bank use, including activities such as angling, livestock grazing and pedestrian access, but not those related to navigation
Category C:	erosion influenced only by factors in Group C, i.e. navigation, lock operations, mooring and activities generating boat wash
Category A-B-C:	erosion influenced by factors from all Groups
Category A-B:	erosion influenced by factors in each of Groups A and B
Category A-C:	erosion influenced by factors in each of Groups A and C
Category B-C:	erosion influenced by factors in Groups B and C.

Consideration of the causes of erosion at each of the 147 sites, in terms of the categories listed in Table 5.8, allows quantification of the factors contributing to erosion along each reach (Figure 5.15) and for the River Thames as a whole (Figure 5.16). The results identify the prevalent factors influencing erosion within each reach and, thus, have value at both the project level (in identifying factors contributing to erosion) and the strategic planning level (in developing effective management objectives) as discussed in Chapter Seven.

Figure 5.17 uses the data from Figure 5.16 to illustrate the bank protection and vegetation characteristics of the eroding sites. This clearly demonstrates the prevalence of erosion associated with bare, unvegetated banks, with erosion progressively decreasing through grassed, shrub, tree-lined and wooded banks. Erosion at protected banks was generally rare (roughly similar or less than that at wooded banks) with only approximately 1km of eroding bankline. An exception concerned erosion of banks protected with bagwork, which amounted to approximately 4km along the length of the River Thames (roughly equal to the extent of erosion of tree-lined banks).

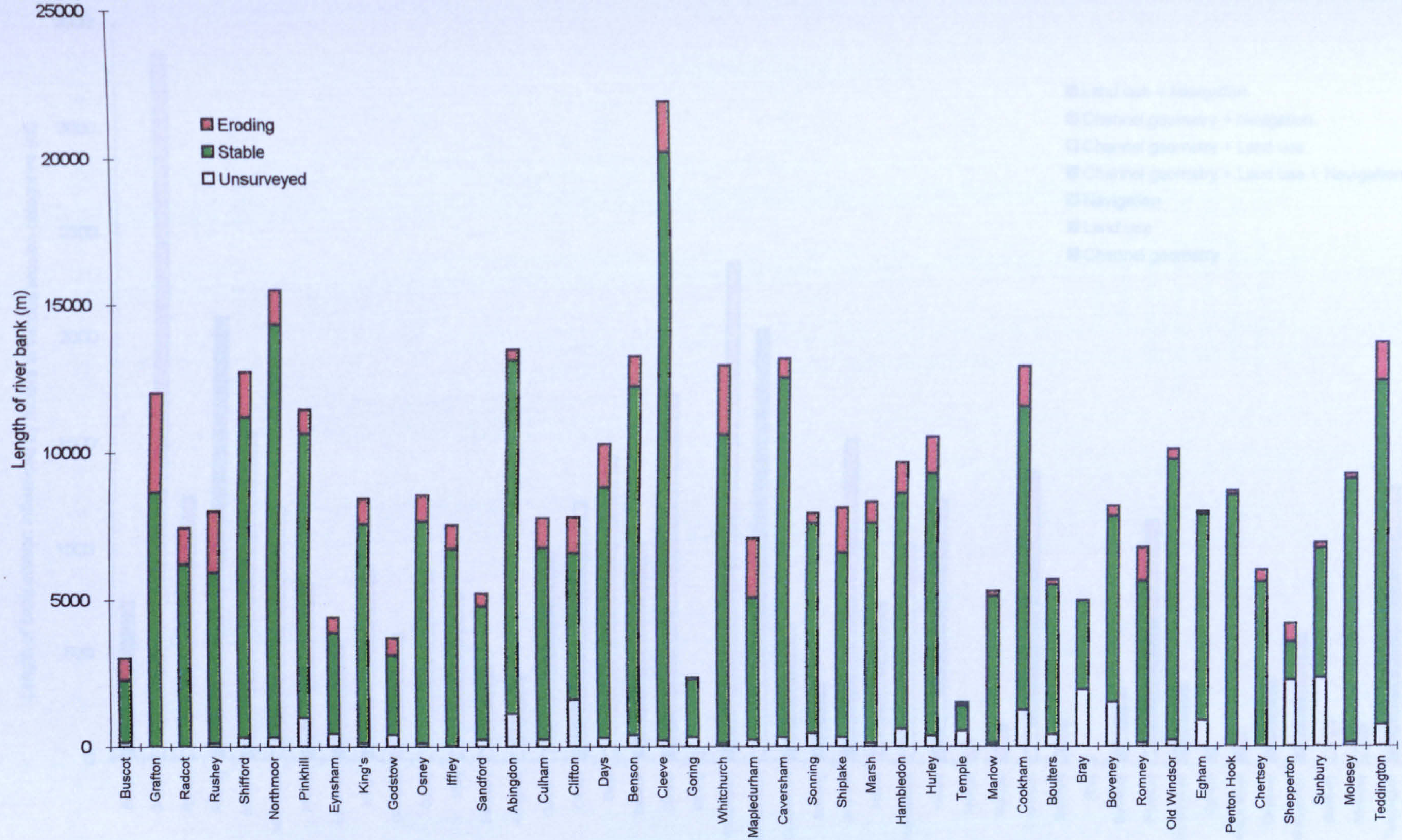


Figure 5.14 Length of bank which is eroding, stable and unsurveyed along each reach of the River Thames, where length of eroding bank is the total length of erosion from 147 sites.

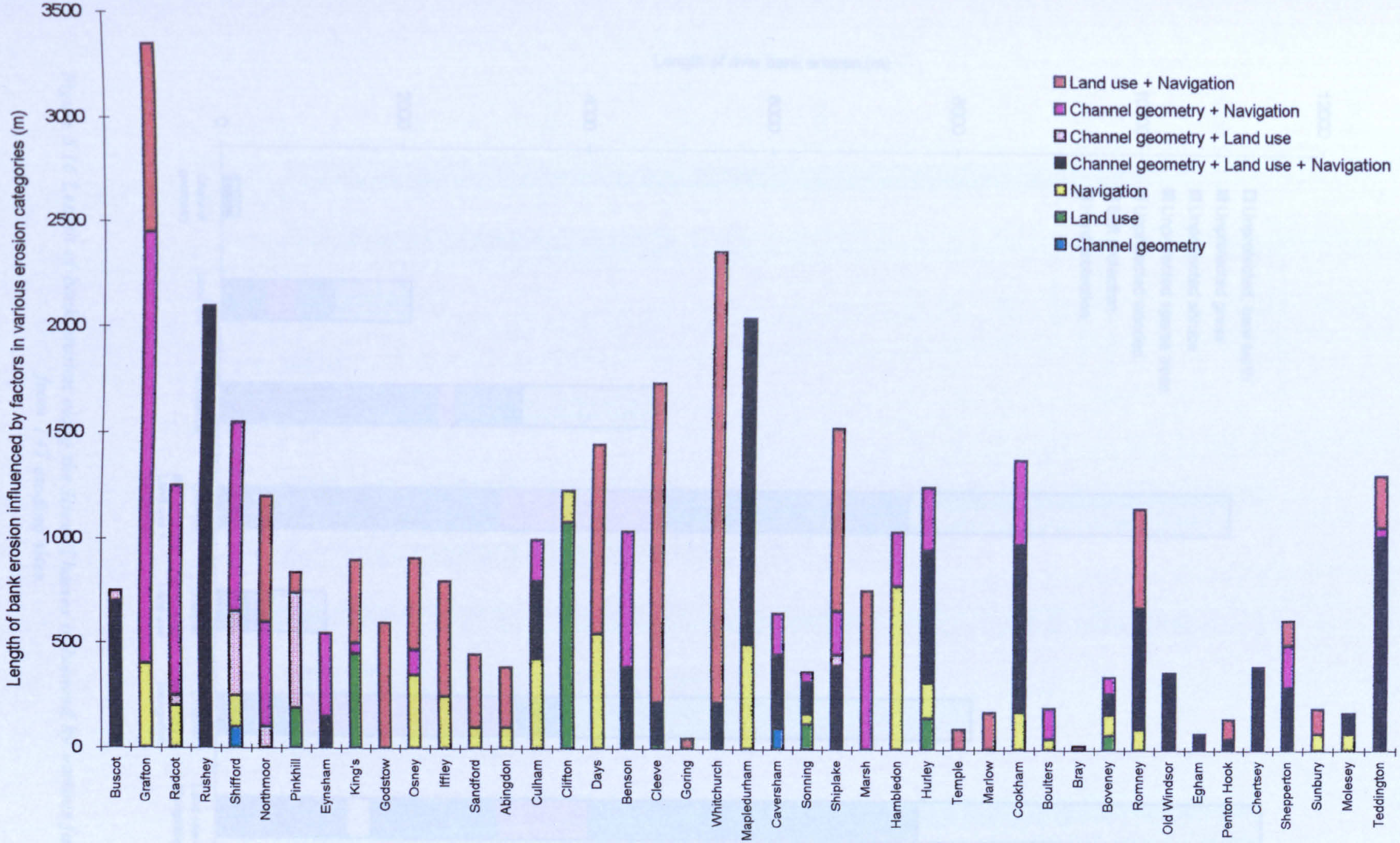


Figure 5.15 Causes of erosion along each reach of the River Thames, from 147 eroding sites

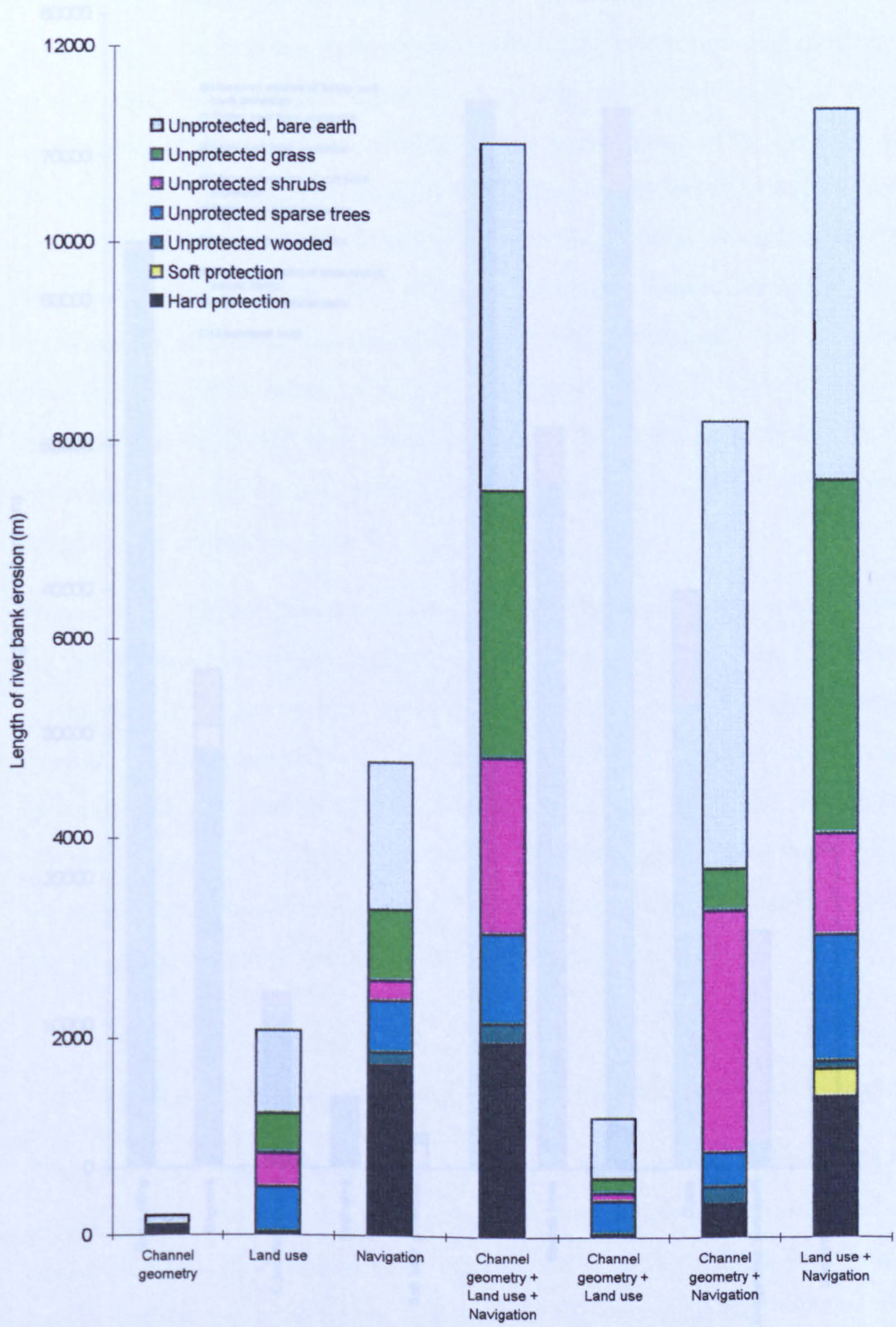


Figure 5.16 Length of bank erosion along the River Thames influenced by various factors, from 147 eroding sites.

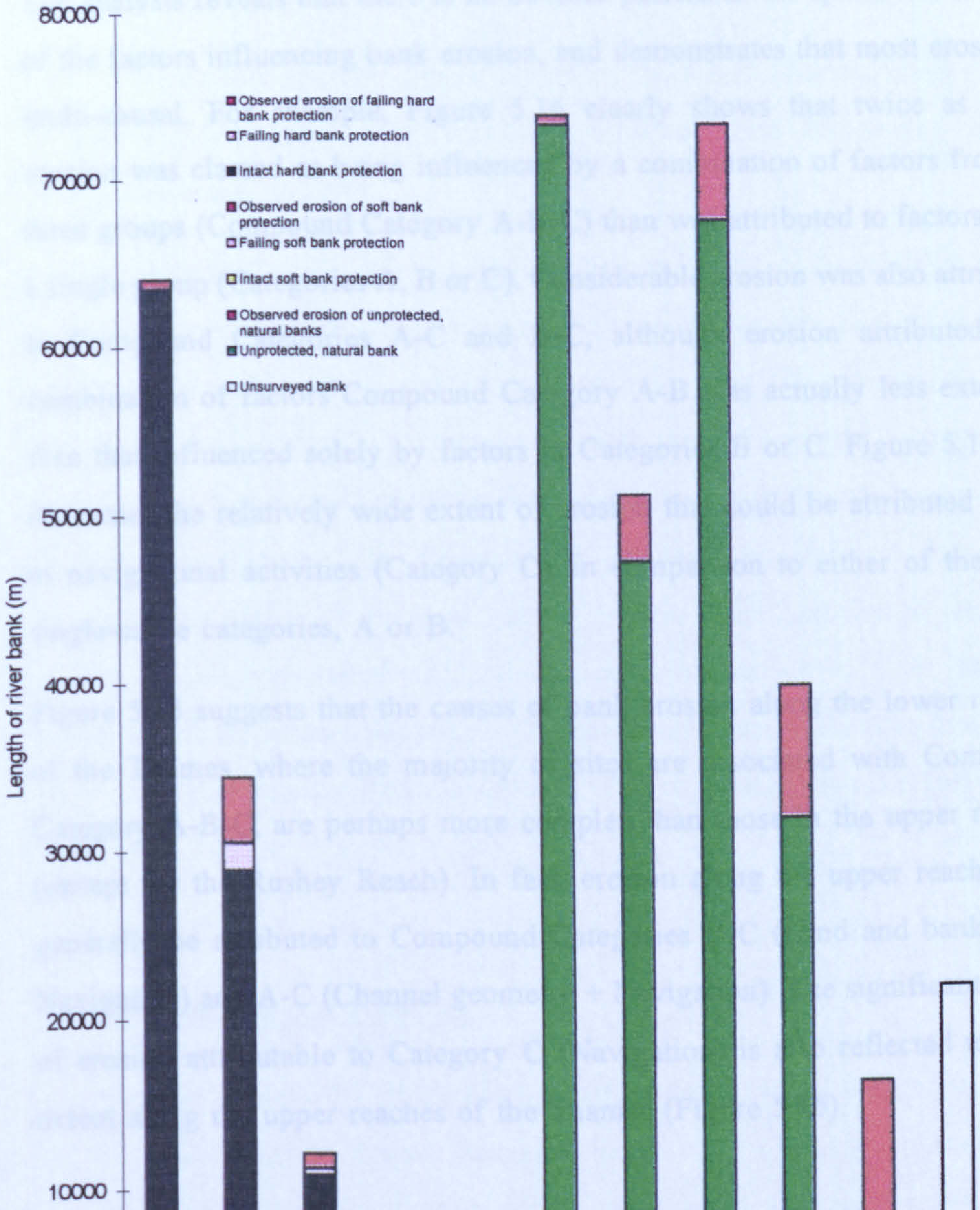


Figure 5.17 Bank characteristics along the River Thames from St. John's to Teddington, where observed erosion is from 147 sites.

The analysis reveals that there is no obvious pattern in the spatial distribution of the factors influencing bank erosion, and demonstrates that most erosion is multi-causal. For example, Figure 5.16 clearly shows that twice as much erosion was classed as being influenced by a combination of factors from all three groups (Compound Category A-B-C) than was attributed to factors from a single group (Categories A, B or C). Considerable erosion was also attributed to Compound Categories A-C and B-C, although erosion attributed to a combination of factors Compound Category A-B was actually less extensive than that influenced solely by factors in Categories B or C. Figure 5.16 also illustrates the relatively wide extent of erosion that could be attributed solely to navigational activities (Category C), in comparison to either of the other single-cause categories, A or B.

Figure 5.15 suggests that the causes of bank erosion along the lower reaches of the Thames, where the majority of sites are associated with Compound Category A-B-C, are perhaps more complex than those in the upper reaches (except for the Rushey Reach). In fact, erosion along the upper reaches can generally be attributed to Compound Categories B-C (Land and bank-use + Navigation) and A-C (Channel geometry + Navigation). The significant extent of erosion attributable to Category C (Navigation) is also reflected to some extent along the upper reaches of the Thames (Figure 5.16).

5.7 Review of factors influencing bank erosion along the River Thames

The two components of assessment reported in this chapter (see Table 5.1) are complementary in that the first provides an overview of the *potential* for various factors to influence bank erosion along each reach of the Thames, whilst the second provides an overview of the factors *actually observed* to influence erosion. The potential and observed influence of each of the factors investigated are now compared.

Discharge and slope

The relatively low specific stream power of the River Thames, as illustrated in Figure 5.1, suggests that large-scale morphological adjustment through fluvial erosion is unlikely.

Measurements of near-bank velocities taken at ~60% of bankfull discharge indicate that bank shear stresses generated by high autumn and winter flows are certainly sufficient to remove soil particles that have previously been loosened by processes of weakening and weathering. They further suggest that high in-bank flows could result in limited erosion of intact bank material, as illustrated in Figure 5.10. Observations of bank erosion and failure are consistent with these findings, and illustrate that significant fluvial erosion is limited to relatively small scale, localised incidents where flow attack is concentrated. No reach-scale morphological adjustments of the type that would occur in higher energy systems (stream powers greater than $35 W/m^2$) were observed.

Channel planform and geometry

The reach-scale sinuosity of the River Thames ranges from 1.0 (Goring Reach) to 1.47 (Godstow and Chertsey Reaches). Several of the reaches with relatively high sinuosities were observed to display a dominance of erosion influenced by factors in Group A (Channel planform and geometry). For example, the Buscot, Rushey, Shifford, Eynsham and Chertsey Reaches all have sinuosities greater than 1.3 and erosion processes that are dominated by Category A, or Compound Categories A-B, A-C or A-B-C. The Godstow Reach is exceptional in that it is the only reach with a sinuosity greater than 1.3, but with no erosion attributed to factors in Group A. In fact, all the observed erosion was attributable to factors in Compound Category B-C.

Reaches with relatively low sinuosity also have a relatively short or no lengths of bank with erosion influenced by factors in Group A. For example, the Iffley, Abingdon, Clifton, Goring, Temple and Bray Reaches all have low sinuosities (< 1.1) and no observed erosion influenced by factors in Group A. Sinuosity along the Osney, Cleeve, Whitchurch and Mapledurham Reaches is also < 1.1 while only a small proportion of observed erosion was influenced by any of the factors in Group A.

This assessment suggests that channel planform and geometry does influence bank erosion along the River Thames to some extent. However, the influence of channel planform and geometry is not dependent exclusively on sinuosity, and at the study sites additional planform and geometry factors, such as flow deflection downstream of weirs and opposite islands, were also observed to contribute to bank erosion. More generally, factors related to channel planform and geometry were found to be inextricably linked to factors from Groups B and C in influencing erosion along the River Thames. This is clearly illustrated in Figure 5.16.

River bank characteristics

The potential for bank erosion was classified on the basis of the physical characteristics of the bank, with 'highly susceptible' representing the banks most vulnerable to erosion. In fact, the extent of bank erosion observed (Figure 5.14) was generally greater than the predicted length of bank classed as 'highly susceptible' (Figure 5.5). This apparent contradiction can be resolved by adding the length of hard bank protection observed to be failing to that 'highly susceptible' to erosion. This step matches the length of potentially vulnerable bank closely to that observed along the Iffley, Culham, Romney and Teddington Reaches.

Figure 5.17 clearly illustrates that the majority of the observed eroding bank line (approximately 15km) along the River Thames coincided with unvegetated, earth banks, classed as 'highly susceptible' to erosion. A further 8km, 6km and 4km of erosion along grass, shrub and tree-lined banks, respectively. Only 1km of erosion was observed along wooded banks. Hence, the observed erosion of unprotected banks supports the original classification of erosion susceptibility presented in Table 5.2.

No link is evident between the potential for erosion by flow deflection and the observed bank erosion. In fact, for the two reaches of the upper Thames where flow deflection potential is relatively high (Iffley and Culham) factors from Group C (Navigation) dominated the observed erosion. Possibly, the high flow deflection potential along these reaches was responsible for exacerbating erosion caused by boat wash.

Land, channel and bank use

The influence on bank erosion of land, channel and bank use included consideration of fishing, pedestrian traffic, amenity access and livestock grazing. The influence of channel use associated with navigation, including boat wash and mooring, was considered separately. Figure 5.15 illustrates the extent to which land use and navigational activities influence bank erosion along each reach. Figure 5.18 shows that, for the entire length of the river included in the assessment, approximately 5% of the observed erosion was influenced solely by land and bank use, while 12% was influenced solely by navigation. Land and channel use factors influence bank erosion primarily along the upper reaches of the Thames, where rural land use includes livestock grazing and where recreational navigation activities tend to be concentrated. These conditions are typified by the Oxford (Osney to Culham Reaches) and Pangbourne areas (Whitchurch and Mapledurham Reaches). Further downstream, fishing, rather than grazing, dominates bank use, but the influence of navigation is still evident, particularly around Henley (Hambledon Reach).

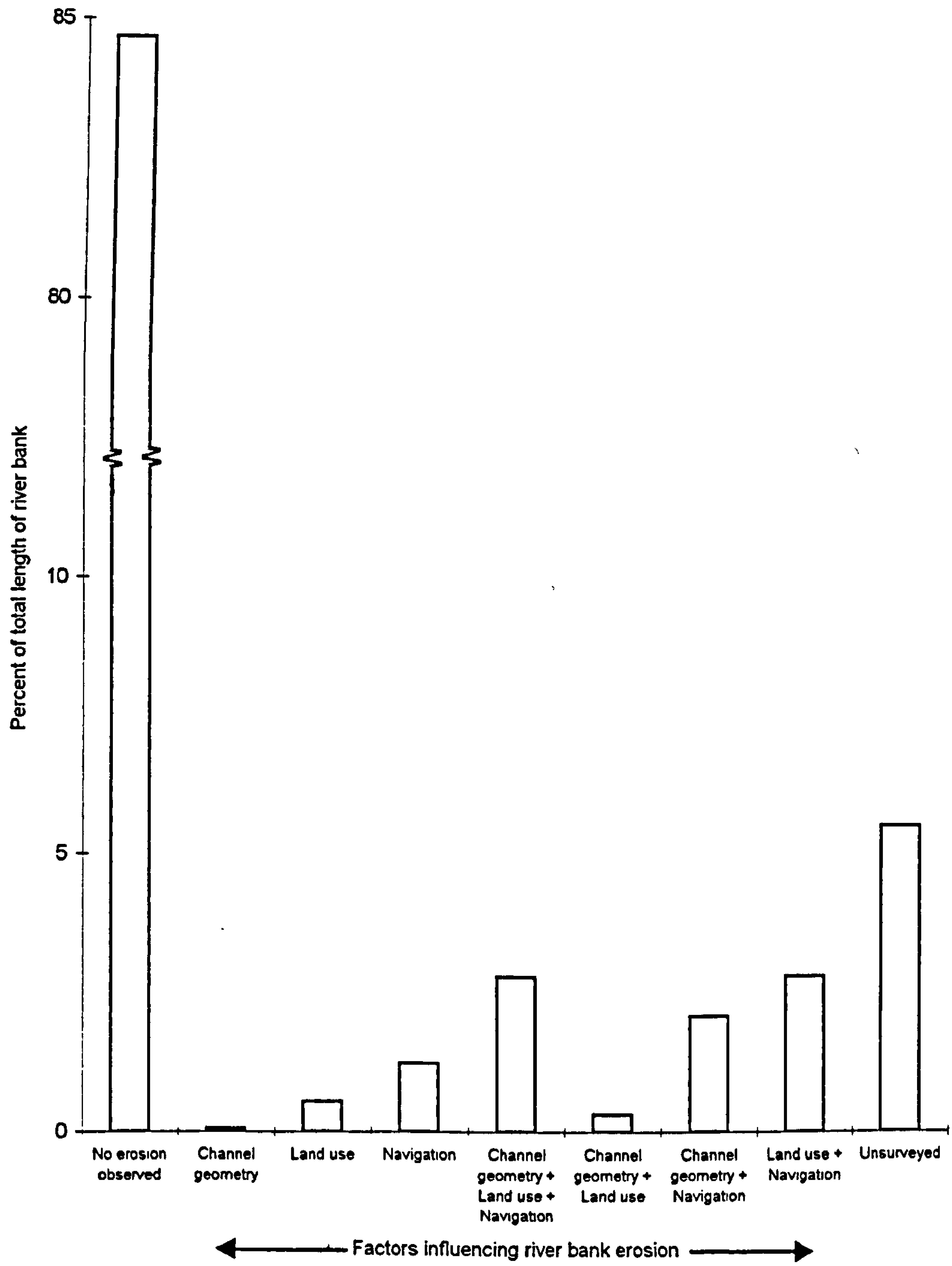


Figure 5.18 The contribution of various factors to bank erosion along the River Thames

Boat wash impact potential (Figure 5.13) appears to have little influence on the causes of bank erosion (Figure 5.15) although many of the reaches with above average wash impact potential (375 boats per metre width per year) also had a majority of the erosion influenced by factors related to navigation. These reaches include Northmoor, Iffley, Abingdon, Day's, Benson, Cleeve and Whitchurch Reaches, whilst the most significant exceptions to this are Egham and Penton Hook Reaches, where little erosion was observed.

The boat wash impact potential is based on the number of craft passing through the locks and does not account for additional vessel activities between the locks. However, such activities can be significant, particularly along lengths of river used for water sports, such as those in the Henley and Oxford areas. Observations of rowers, for example, indicate that, although the wash generated by the majority of craft is generally of low magnitude, training exercises are often escorted by a small speed boat. During a typical training session, the speed boat may travel up and down the river many times. Such speed boats often generate wash against the banks that is much stronger than that associated with cruisers (for example, see Plate 5.1). Whilst cruiser traffic is unlikely to generate sufficiently high bank shear stresses to result in erosion (see "characteristic" results in Figure 5.10), the "uncharacteristic" wash generated by training boats is likely to erode the bank. On this basis, the uncharacteristic boat wash associated with sports boats probably contributes significantly to the bank erosion observed in the vicinity of Oxford, Henley and other popular centres for water sports.

Conclusions

This assessment of bank erosion along the River Thames suggests that the river's planform is generally stable with no tendency for reach-scale adjustments through bank erosion. Over 90% of the bankline is either stable or is not eroding significantly. Sites experiencing erosion are localised.

A total of about 38.5km of river bank was identified as eroding to some degree, which represents nearly 10% of the total length of bank. Evaluation of the factors influencing erosion at 147 study sites along the main channel between St. John's and Teddington, indicates that erosion is influenced by channel planform and geometry; land, channel and bank use and navigation-related activities.

Erosion along approximately 12% of the eroding length was caused solely by factors related to navigation activities. In addition, navigation-related activity was a contributory factor in over 90% of the observed cases of bank erosion. Approximately 5% of the erosion was attributable solely to land and bank use, although these factors contributed to erosion at approximately 65% of the sites. Only 0.5 % of the observed erosion was caused solely by channel planform and geometry, although these factors contributed to erosion at over 50% of the study sites. The influence of the various factors on bank erosion along the River Thames is summarised in Table 5.9.

The majority of erosion was observed to occur on unvegetated banks. There were decreasing amounts of erosion on grass, shrub, tree-lined and wooded banks. This clearly reflects the effects of vegetation in reducing the incidence of bank erosion, although the mechanisms are poorly understood. However, it is reasonable to deduce, for example, that a wooded bank will probably deter recreational access to a greater extent than a grassed bank and will, therefore, not be subjected to intense pedestrian traffic, with its potential for erosion.

Table 5.9 The influence of various factors on bank erosion at 147 sites along the River Thames.

Factors influencing bank erosion	Length of bank erosion (m)	Percent of total length of bank erosion
Category A: Channel planform and geometry	200	0.5
Category B: Land and bank use	2080	5.4
Category C: Navigation	4770	12.4
Compound Category A-B-C: Channel planform and geometry + Land and bank use + Navigation	11010	28.5
Compound Category A-B: Channel planform and geometry + Land and bank use	1200	3.1
Compound Category A-C: Channel planform and geometry + Navigation	8210	21.3
Compound Category B-C: Land and bank use + Navigation	11100	28.8

CHAPTER SIX

SOLUTIONS TO BANK EROSION PROBLEMS ON THE RIVER THAMES

6.1 Introduction

It is not a difficult engineering challenge simply to prevent the banks of the River Thames from eroding. The greater challenge is to identify the optimum solution to a bank erosion problem with regard to efficacy, cost and environmental-acceptability.

The previous chapters analysed the processes and mechanisms acting in the bank zone and their influence on erosion. This chapter reviews alternative solutions to bank erosion problems on the basis of an understanding of these processes and mechanisms and the application of that knowledge in selecting an optimum solution.

Section 6.2 briefly reviews the development of a classification of alternative erosion management strategies and a framework for the selection of solutions to bank erosion problems on non-tidal rivers. The classification and framework were recently developed by the Environment Agency (1997) to facilitate consideration of alternative options in light of geomorphological constraints and the processes and mechanisms of erosion discussed in previous chapters.

Section 6.3 critically reviews selected case studies where alternative erosion control techniques have been applied along the banks of the River Thames. The chapter concludes by reporting on the success of the case studies in terms of (1) their appropriateness in light of the processes and mechanisms of erosion and (2) their fulfilment of the broad aims of environmental assessment as practised by the Environment Agency, Thames Region (NRA, 1994a).

6.2 Classification and selection of erosion control strategies

'Hard' engineering techniques, such as steel piling and concrete, have been used extensively along the banks of many rivers in the UK for flood defence and erosion control (Brookes, 1988). However, recently there has been a move towards encouraging the use of more environmentally sensitive approaches to bank protection (eg. Hey *et al.*, 1991; Glynn *et al.*, 1994; RSPB/NRA/RSNC, 1984; 1994; Goodwin, *et al.*, 1995).

In particular, the Environment Agency (and its predecessor, the National Rivers Authority), British Waterways and the Broads Authority have undertaken collaborative research to investigate bank erosion problems on rivers and canals and developed guidelines for its management. This research and development (R&D) has comprised three phases. Phase I was essentially a review of literature relating to bank erosion and methods of bank protection (NRA, 1991). Phase II involved monitoring bank erosion and a review of selected erosion control techniques applied along a number of navigable rivers. Phase II culminated in procedural and policy guidance for the assessment of bank erosion problems and the selection of appropriate solutions (NRA, 1996; NRA, 1994c). Phase III progressed the research findings from Phase II to developed detailed operational guidelines to address bank erosion problems on tidal and non-tidal rivers and canals (Environment Agency, 1997).

The author was the Research Associate for Phase II of this collaborative R&D project, which was undertaken by Nottingham University. During Phase II the author monitored erosion at the seven sites on the River Thames discussed in Chapter Four and a further twelve sites on the Rivers Trent, Medway and Great Ouse and the Norfolk Broads (NRA, 1994b). The author also reviewed the performance of erosion control techniques at 31 sites also on the Rivers Thames, Trent, Medway and Broadland rivers (NRA, 1994b). Whilst Section 6.3 reports some of the erosion control techniques applied along the River

Thames and reviewed in NRA (1994b), those applied along other rivers are not reported in this thesis (see Appendix 6.3). Nonetheless, the author has used experienced gained during Phase II in order to evaluate the appropriateness of the erosion control techniques reported in Section 6.3.

The author also contributed to Phase III of the R&D project as an Environment Agency steering group member and has gained considerable experience in the application of erosion control techniques whilst employed by the NRA and Environment Agency (Thames Region) as a geomorphology specialist.

In the past, authors have used different criteria to distinguish bank protection categories (eg. Hemphill and Bramley, 1989; RSPB/NRA/RSNC, 1984; 1994; NRA, 1991). For example, Hemphill and Bramley (1989) made the distinction between natural bank protection, vertical protection and other revetments, while NRA (1991) distinguished between three protection methods: (1) armoured revetments, (2) protection using a hard interface between the river and the bank, and (3) techniques involving construction principally within the channel. Later, Phase II of the Environment Agency's R&D project categorised structural intervention into hard and soft techniques and hybrids of the two (NRA, 1996). The bank erosion monitoring and review of erosion control techniques undertaken by the author during Phase II suggested that erosion control techniques were not always appropriate for the causes of erosion and solutions were often 'over-engineered'. Furthermore, this research suggested that erosion could, in many circumstances, be 'managed' without the necessity for structural intervention. NRA (1996) described the contribution of 'management solutions' to solving erosion problems, such as 'allowed natural adjustment', eliminating the problem or risk associated with the erosion, and reducing the intensity of erosion by, for example, fencing a bank to prevent livestock grazing and limiting navigation speeds to reduce boat wash.

Phase III of the R&D project developed a hierarchy of erosion management strategies and a framework for deciding the most appropriate techniques to address a bank erosion problem (Environment Agency, 1997). These six strategies are listed in Table 6.1, with a brief description of the overall approach taken by the strategy.

Table 6.1 Six erosion control strategies from Environment Agency (1997)

Erosion Control Strategy	**Description**
1. Allowed natural adjustment	Allows the bank erosion to continue without intervention
2. Management	Addresses (through active management) the cause of the erosion problem, eg. by reducing boat speeds to reduce the impact of boat wash on bank erosion, or by fencing off the bank to prevent access or poaching by livestock
3. Relocation	Relocates the asset at risk from erosion to a less vulnerable site, eg. by realigning a footpath away from an eroding bank
4. Bioengineering	Uses vegetation to stabilise the bank, eg. reeds, willows, shrubs and trees
5. Biotechnical engineering	Uses vegetation in combination with other materials to stabilise the bank, eg. geotextiles, pocket fabrics, rock and fibre rolls, open cell revetments
6. Structural engineering	Uses 'hard' engineering materials (as opposed to vegetation) to stabilise the bank, eg. gabion baskets, steel and concrete, and includes flow control structures placed within the channel, eg. groynes

The framework devised by the Environment Agency (1997) hinges on a preference hierarchy for the six erosion control strategies, based on sustainability principles. In the hierarchy, the first strategy in Table 6.1, 'allowed natural adjustment', is the most preferable and the last strategy, 'structural engineering', is the least preferable.

The framework guides the user through a series of investigative steps during which information is compiled regarding:

i) the mechanisms of bank failure;
ii) the severity of the consequences of bank erosion;
iii) the major causes of erosion;
iv) the average bankfull velocity;
v) the bank loading, height and slope.

The framework consists of two key stages: first, identification of the appropriate strategy and, second, determination of the most appropriate technique. In the first stage, information relating to items i), ii) and iii) above is used in a single decision tree to determine which of the six strategies would be most appropriate to address the causes of erosion within the site constraints (see Appendix 6.1). A risk-based approach is taken which requires the user to combine the causes of erosion and mechanisms of failure with the risk of continued erosion and any other issues to be addressed such as wildlife, recreation, navigation and flood defence. The decision tree allows the erosion problem to be judged as 'moderate', 'important' or 'severe', depending on the consequences of erosion.

In the second stage, information relating to items iv) and v) above is used to determine which protection techniques within each strategy would be suitable for use in a particular river and bank environment. The framework uses decision trees to describe the limitations of the different solutions within a strategy according to the bank loading, height and angle and the average velocity at bankfull flow (see Appendix 6.2). Whereas the application of strategies 1, 2 and 3 is unconstrained by flow velocities, bank loading or bank geometry, the use of strategies 3, 4 and 5 (bioengineering, biotechnical engineering and structural engineering) may be limited by the river and bank environment. Consequently, a decision tree is used to describe the limitations of the alternative techniques within each of strategies 4, 5 and 6. Hence, there is a total of three decision trees in the second stage (see Appendix 6.2).

Each solution must be accompanied by success criteria which are specified during the design phase of the project. Typically, these success criteria include health and safety, engineering, economic and environmental considerations. Naturally, the type of geomorphological evaluation described by Brookes *et al.* (1998) will contribute to the overall post-project appraisal which includes monitoring and audit against the range of success criteria specified during the design of the solution.

Perhaps one of the most valuable elements of the Environment Agency's (1997) framework is its transparency. This allows the user to investigate the sensitivity of the selected solution to the various decisions made during each stage of the procedure. Conversely, one drawback of the decision trees shown in Appendix 6.2 is that they do not allow the user to identify easily the limitations to a specific technique, although they do allow the user to fairly rapidly review the outcome of decisions under different scenarios. For example, if the angle of the bank is a limiting factor in the selection of a solution, the user can quickly review the alternatives that would be available if the slope were reduced. The framework was developed as guidance for bank erosion problems on tidal and non-tidal rivers and canals, and the format in which the guidance is presented is entirely appropriate for this broad range of waterways.

6.3 Case studies of alternative erosion control techniques

Numerous types of bank protection technique have been employed along the River Thames and other UK rivers (eg. NRA, undated b; Smith, 1994; Goodwin, 1995; Environment Agency, 1997). Valuable experience regarding the limitations of these techniques can be gained by reviewing the performance of the protective methods in different river and bank environments. In deriving the decision trees described above, the Environment Agency (1997) reviewed a large number of case studies from the UK and from the relevant literature (eg. RSPB/NRA/RSNC, 1984; 1994; Hemphill and Bramley, 1989; Schiechtl and Stern, 1997), including the techniques reviewed by the author during Phase II of the R&D project (NRA, 1994b).

This section uses case studies to review several of the erosion control strategies that have been employed along the banks of the River Thames. A total of 21 case studies has been recorded, including techniques from strategies 4, 5 and 6 in Table 6.1. Studies cover bioengineering techniques such as willow spiling, biotechnical engineering techniques such as geotextiles, and structural engineering techniques such as gabion baskets and riprap. In addition, one example of strategy 1, allowed natural adjustment, and one example of strategy 2, management, have been recorded. Unfortunately, no case studies of strategy 3, relocation, have been recorded along the Thames. The case studies are listed in Table 6.3, according to the reach of the River Thames within which the site is located. The locations of the case studies are listed in Table 6.2 and are also shown on the relevant maps in Volume III.

For many of the monitoring sites, installation of the protective measures may be too recent to allow an unequivocal assessment of the success or failure of the technique. To achieve this, further monitoring over a longer time period is required. Furthermore, after implementation of a project it is often difficult to obtain information concerning the condition of the bank prior to engineering work, or the precise reasoning behind the selection of a strategy and the design of the solution. Nonetheless, the appropriateness and performance of the case studies was assessed as far as possible, against five criteria (see Section 6.4 and Appendix 6.5):

i) whether the strategy implemented in the case study is the same as that which is suggested using (retrospectively) the decision framework developed by the Environment Agency (1997);

ii) whether the technique has performed as expected, i.e. remained *in-situ* and experienced no erosion or failure;

iii) whether there were any alternative, more appropriate techniques or additional measures that would have improved the performance of the technique;

iv) whether negative impacts were adequately mitigated, according to the aims of environmental assessment (NRA, 1994a);

v) whether environmental enhancements were incorporated, according to the aims of environmental assessment (NRA, 1994a).

Table 6.2 Erosion control case studies along the River Thames

Case study number and river reach		Erosion control strategy (numbered 1 to 6 - see Table 4.1) and specific technique		Site location (see Volume III)	
				Map	NGR
1	Godstow	5	: geotextile + spiling	10	448209
2	Godstow	6	: gabion baskets	10	448209
3	Sandford	6	: sheet piling + riprap	13	452203
4*	Clifton	1	: allowed natural adjustment	16	450194
5	Clifton	5	: geotextile + spiling	16	454194
6	Clifton	4	: spiling	16	454194
7*	Clifton	6	: sheet piling	16	454194
8	Cleeve	5	: geotextile + spiling + willow	19a	461189
9	Cleeve	6	: gabion mattress/riprap+geotextile	19a	461190
10	Goring	5	: geotextile	20	459181
11	Mapledurham	2&4	: spiling + fencing	22	464177
12*	Caversham	4	: faggots	23	466176
13	Marlow	5	: geotextiles	30	484184
14	Marlow	4	: spiling	30	484185
15*	Cookham	6	: sheet piling + riprap	31	486185
16*	Cookham	4	: spiling	31	489185
17*	Boulter's	6	: piling + gabion baskets	32	489185
18*	Egham	4/6	: faggots / gabion baskets	37	499174
19	Egham	6	: gabion baskets	37	500172
20	Shepperton	6	: gabion baskets	40	505166
21*	Teddington	4/6	: faggots / riprap	43	516171

* denotes cases in which the author was part of the design team

This section reviews each of the case studies in turn, while Section 6.4 reports on the performance of the case studies against the above criteria. Appendix 6.4 lists the assumptions made about each site in using the framework developed by the Environment Agency (1997). The framework developed by the Environment Agency (1997) is used here for two reasons. Firstly, because the author participated throughout Phases II and III of this research and, therefore, fully endorses the approach taken. Secondly, because the framework will be implemented by the Environment Agency as national guidance and will, therefore, be adopted at a local level. Recognising that there is a move towards developing standard approaches to the application of geomorphology in river management (Brookes, 1995; 1996), it would be impractical to develop an alternative approach. In fact it is logical to draw on the methodology that has already been endorsed, and is soon to be adopted, by the Environment Agency.

<u>Case study no. 1</u> **Godstow Reach: Volume III - Map 10 NGR:448209**

Strategy 5: biotechnical engineering (geotextile + spiling)

This site is located along the right bank upstream of Godstow Lock (see Volume III, Map 10). A combination of willow spiling and Nicospan geotextile was used to protect the bank, but the specific consequences of continued erosion are unknown (see Appendix 6.4). The spiling has remained intact in places where the bank was fenced, but the majority of the protection has suffered significant mechanical damage from poaching by cattle which graze the site (see Plate 6.1).

Whilst the condition of the bank prior to protective measures is largely unknown, the bank geometry would suggest that mass failure was not experienced along this length of bank. Land use adjacent to the bank is pasture, therefore the consequences of the erosion at this site can be considered 'moderate', with animal activity being the major cause of erosion (see Appendices 6.1 and 6.4). Under such circumstances the Environment Agency's (1997) framework suggests that only strategies 1, 2 and 3 house appropriate solutions.

Plate 6.1
Case study no.1:
Failed spiling and Nicospan geotextile along Godstow Reach

One alternative may have been to take no action and allow the erosion to continue (strategy 1: allowed natural adjustment) because there were no assets at risk on the adjacent land. Erosion monitoring at St. John's (see Chapter Four) suggested that rates of erosion resulting from similar cattle trampling were of the order of 0.15m per year. However, trampling also resulted in significant mechanical damage which contributed to erosion of weakened bank material by fluvial entrainment. Consequently, a more successful solution to the problem of cattle trampling would have been to use fencing to restrict cattle access to vulnerable locations and allow natural vegetation to colonise and help stabilise the banks. A sacrificial length of bank would be required to maintain access to the river for livestock watering. This length could either be allowed to erode or protected with an engineering structure, if the consequences of erosion were considered sufficiently 'severe' (see Appendix 6.1). The most appropriate of the engineering solutions recommended by the Environment Agency's (1997) framework would be rock rolls and open cellular revetment because the bioengineering structures and the majority of the biotechnical engineering structures cannot tolerate cattle trampling. Whilst these bioengineering techniques would provide structural stability, the more natural appearance of riprap would probably offer a preferable solution on aesthetic grounds.

<u>Case study no. 2</u> Godstow Reach: Volume III - Map 10 NGR:448209

Strategy 6: structural engineering (gabion baskets)

This site is along the left bank of Godstow lock cut, upstream of the lock. The condition of the bank prior to the works is unknown, nor is the severity of the consequences of failure. However, the bank is part of the lock island and it is, therefore, likely that the consequences of erosion would be considered 'important' due to the limitations on land area. In these circumstances the Environment Agency's (1997) framework recommends strategies 2 and 4 (see Appendices 6.1 and 6.4).

Located along the lock cut, this site would be expected to experience intensive boat traffic at relatively low speeds. The boat wash monitoring experiment reported in Chapter Five suggested that craft travelling at low velocities would be unlikely to result in erosion of intact bank material but may cause sufficient near-bank velocities to remove weakened particles from the surface of the bank. It is likely that the face of the bank was unvegetated prior to installation, and that, similarly to the observations of erosion at the Upper and Lower Wallingford monitoring sites (Chapter Four), weakening of the exposed surface of the bank material and, in particular, at the level of the water surface, resulted in bank erosion. Gabion baskets were installed to protect the bank (see Plate 6.2), whereas the bank could have been regraded and protected with the use of a bioengineering solution such as rock-filled rolls. It may be the case that the landowner wished to maintain a vertical bank or that regrading the bank to a stepped profile would have resulted in unacceptable damage to bank-side trees or would have constituted a hazard to navigation. Even without regrading, willow spiling would have provided adequate protection to the bank.

Plate 6.2
Case study no. 2: gabion baskets at Godstow lock island

Case study no. 3 **Sandford Reach: Volume III - Map 13 NGR:452203**

Strategy 6: structural engineering (sheet piling + riprap)

This site is located along the left bank downstream of Iffley Lock. A vertical bank was required below the level of the water for navigation purposes and hence, steel sheet piling was used to protect the bank. Above the water level riprap was placed on the bank which was graded to a slope. Reeds were planted within the riprap at the level of the water surface (see Plate 6.3).

Plate 6.3
Case study no. 3: sheet piling below water level with riprap and reed planting (taken December 1996)

The protective measures were installed in Spring, 1996 and hence, it may be some years before vegetation fully colonises the riprap. Nonetheless, the measures would be expected to withstand the relatively low flow velocities but intensive boat traffic near to the lock. With 'important' consequences of erosion, the Environment Agency's (1997) framework suggests that strategies 2 or 4 are appropriate and that a bioengineering solution such as willows would have been suitable. Under 'severe' consequences of erosion, gabion baskets could have been used as an alternative to sheet piling along the vertical lower bank. However, despite the ecological benefits of gabion baskets, the Environment Agency's (1997) framework makes no preference between these and other structural engineering techniques such as sheet piling.

The low flow velocities expected at this site also suggest that a geotextile pocket fabric would have been an appropriate alternative to riprap along the sloping upper bank. Both riprap and pocket fabrics have ecological potential.

It could be argued that the use of riprap is more environmentally sensitive than the use of non-biodegradable geotextiles because loose stone riprap is a more natural material. However, the preference hierarchy suggests that a bioengineering solution is more favourable than a structural engineering solution, and hence that geotextile pocket fabric would have been more appropriate solution along the upper bank. Furthermore, whereas the use of loose stone revetments along some rivers can complement the natural river landscape, the geology and landscape character of the River Thames does not lend itself to the use of natural stone bank protection. In this case, a more appropriate solution would have been to use coir rolls, constructed from coconut fibre, planted with reeds at the level of the water surface and grass and shrub planting above this level.

Case study no. 4 **Clifton Reach: Volume III - Map 16 NGR:450194**

Strategy 1: allowed natural adjustment (no action)

An erosion problem was identified downstream of Culham Weir. This problem was investigated by the Environment Agency's Project Engineers in conjunction with its environmental specialists. The author participated as the geomorphology specialist in the design team in the way described by Brookes (1995). The author's assessment of the site suggested that the toe of the bank was, in fact, stable and that, whilst the upper bank was relatively poorly vegetated, the bank material was relatively resistant. Similarly to the Upper and Lower Chertsey monitoring sites (Chapter Four), although the face of the bank appeared to be eroding, the rate of retreat was relatively slow (<0.1m per year). Furthermore, the adjacent agricultural land use was able to accommodate any future diversion of the existing public right of way. Consequently, the site was allowed to adjust naturally. Plate 6.4 shows erosion behind sheet piling which is immediately downstream of Culham Weir.

Plate 6.4
Case study no. 4: erosion of the upper bank downstream of Culham Weir

<u>Case study no. 5</u> **Clifton Reach: Volume III - Map 16 NGR:454194**

Strategy 5: biotechnical engineering (geotextile + spiling)

This site is along the outside of a bend, immediately upstream of Clifton Weir. Nicospan geotextile and willow spiling were installed in spring 1988. The protection remained intact along the majority of the site but, by 1994, a length of protection had failed (see Plate 6.5). The Nicospan along the bank where channel curvature was greatest appeared to be undercut at the toe of the bank.

This length of bank protects the peninsula of land which supports Clifton Weir. The minimum width of the peninsula was approximately 15m and there was, therefore, no immediate risk of breaching the peninsula. However, the medium to long-term consequence of continued erosion would be a breach this peninsula, with significant implications for flooding downstream. Understandably, in the light of the associated human risk, the Environment Agency's (1997) framework does not allow for the consequences of bank erosion on flood defence works to be anything other than 'severe'. The measure of severity in the Environment Agency's (1997) first decision tree (see Appendix 6.1) was intended to allow the merits of a strategy to be weighed against the risks associated with its failure. However, in this instance, failure of any protection measures would not (for many years) result in a breach of the flood defence, or an emergency situation whereby works would be required to prevent imminent disaster. Consideration of the *rate of erosion* is, therefore, extremely important in correctly deciding on the severity of the problem.

Plate 6.5 Case study no.5: Nicospan geotextile and willow spiling upstream of Clifton Weir

As the consequences of erosion were 'severe', and accepting that fluvial processes were the major drivers of slab or cantilever failure, then the Environment Agency's (1997) framework recommends the use of strategies 5 or 6. Incorporating river and bank characteristics (see Appendix 6.4) the Environment Agency (1997) recommends that timber, rock and fibre rolls or open cell revetments would be suitable biotechnical engineering solutions. However, it also suggests that willows would be appropriate if the consequences of erosion were 'important' as opposed to 'severe'.

Failure of the protection may have occurred because the willow stakes were not driven to a sufficient depth in the bed to withstand scour at the toe of the bank. Whereas the failed spiling was subsequently replaced by sheet piling, an alternative solution could have been to regrade the bank to a terraced profile, so reducing near-bank flow velocities. Willow spiling could then be installed along the terraces with rock filled rolls at the toe and tree planting across the middle of the peninsula of land for long-term stability. Boats tend not to travel close to the bank here because the site is so close to the weir and some distance from the approach to the lock cut. Hence, the stepped bank would not be hazardous to navigation. However, failure of parts of the original spiling understandably reduced the design engineer's confidence in the use of vegetation at this site. A compromise solution would have been to use gabion baskets or mattresses at the toe of the bank with a bioengineering structure such as faggots above the gabion. Similar designs to this have been used successfully in high energy environments on the River Medway (Smith, 1998).

<u>Case study no. 6</u> **Clifton Reach: Volume III - Map 16 NGR:454194**

Strategy 4: bioengineering (spiling)

This short length of spiling was installed prior to 1994 at the entrance to Clifton Lock cut, which is downstream of the effects of flow over Clifton Weir (see Volume III - Map 16). The character of the bank prior to protection is not known although the spiling probably resulting in minimal change to geometry. The causes of erosion and failure mechanisms are also unknown but the bank is at the entrance to the lock cut and immediately downstream of concrete-capped sheet piling which protects the upstream of the lock island (see Plate 6.6). Because the site is at the entrance to the lock cut and, therefore, experiences relatively low flow velocities all year round, it is likely that the major cause of erosion was wash from boat traffic. Similarly, to the erosion monitoring sites at Lower Wallingford, Laleham and Chertsey, a spending beach was developing at the toe of the bank. Furthermore, the hard engineering structure upstream will also tend to increase turbulence at the bank, which can lead to the erosion often observed upstream and downstream of structures.

Plate 6.6
Case study no. 6: willow spiling at the entrance to Clifton Lock cut

The consequences of failure were also unknown at this site. However, the lock keeper uses the bank to moor against and it may be that the main reason for installing the spiling was to provide a mooring facility for the lock keeper. Again, the boat wash monitoring exercise (Chapter Five) suggested that boat wash generated by traffic travelling at relatively low speeds, as expected along the lock cut, would not result in sufficient near-bank velocities to erode intact bank material. However, similar wash could be expected to result in erosion of weakened material on the surface of the bank. Under these relatively low shear stresses a bioengineering solution, such as willow spiling, was an appropriate technique to use to prevent continued erosion. Indeed, under these 'moderate' consequences of erosion, the Environment Agency's (1997) framework recommends that strategies 2 or 4 are appropriate and that willows, faggots or tree and shrub planting would prove equally satisfactory solutions.

Case study no. 7 Clifton Reach: Volume III - Map 16 NGR:454194

Strategy 6: structural engineering (sheet piling)

This case study is located along Clifton Lock cut. The Environment Agency, as the navigation authority, wished to accommodate the passage of two Dutch barges along Clifton lock cut. The option to implement a traffic management plan (traffic lights for example) was considered inappropriate. Consequently, dredging of the channel bed was required to increase the navigation width by several metres. The dredging would result in over-steep banks which would then require stabilisation.

The author participated as the geomorphology specialist in the design team for this project in the way described by Brookes (1995). During the environmental assessment of the project various options were considered to increase the navigation width of the channel. These included dredging of the shallow margins along the left or right banks, or along both banks but to a lesser extent. Mature trees along the right bank meant that there was a preference for dredging along the left bank. A public path runs along the left bank, hence the consequences of continued erosion could be considered 'important'. The Environment Agency's (1997) framework therefore recommends the use of strategies 2 or 4.

Whilst the option to regrade the bank to a more stable profile was proposed by the author, it was not supported by conservation staff within the project team because this option would have involved the destruction of the existing bank vegetation (primarily hawthorn trees approximately 20 years old). The Environment Agency owns the land along the left bank and would, therefore, have faced none of the usual challenges when negotiating with riparian owners over compensation payments for land-take.

A further alternative considered was willow spiling, but the bed of the channel was too hard to drive in willow stakes. A compromise solution that was considered was to drive vertical steel stakes into the hard bed and then to weave willow withes around the stakes. However, the Project Manager decided to use sheet piling because a supply of sheet piles was already available. Whilst such decisions may be understandable, this approach to decision making does not necessarily reflect the 'good practice' approach advocated by the Environment Agency (1998a).

Mitigation measures were designed into the scheme, including a low-level shelf above the piling where reeds were planted in coir rolls behind concrete bagwork (see Plate 6.7). However, the boat wash monitoring exercise (Chapter Five) suggests that the use of a bioengineering solution would have been more appropriate for the low energy environment along the lock cut.

Plate 6.7
Case study no. 7: sheet piling and concrete bagwork along Clifton lock cut. Mitigation measures included reed planting in coir rolls on a low-level shelf.

Case study no. 8 **Cleeve Reach: Volume III - Map 19a NGR:461189-190**

Strategy 5 : biotechnical engineering (geotextile + spiling + willow stakes)

This site is along the right bank upstream of Wallingford Bridge and corresponds to the Upper Wallingford bank erosion monitoring site described in Chapter 4. Respectively, Plates 6.8 and 6.9 show slumping of the bank in

December 1992 and the willow spiling protection installed by South Oxfordshire District Council at the beginning of 1995. A combination of techniques was employed along this stretch of bank, but this case study deals with the willow and geotextiles installed along the majority of the length. Case study no. 9 deals with the structural engineering techniques installed at the upstream end of the site.

Plate 6.8 Case study no.8: bank slumping upstream of Wallingford Bridge, December 1992

Plate 6.9 Case study no. 8: willow spiling protection along regraded bank, May 1996

The protection measures were installed in order to maintain a safe footpath along the top of the bank. Judging the consequences of slab failure here as 'important', the Environment Agency's (1997) framework recommends the use of strategy 4 (see Appendices 6.1 and 6.4).

In this case, the fence could have been moved with the landowner's consent and the footpath relocated away from the edge of the bank (see Plate 6.10). Whilst such a relocation strategy would not address the causes of the erosion, it would address the threat to safety posed by erosion of the footpath. The bank was, in fact, regraded to a stepped profile and a combination of Nicospan and Enkamat geotextiles was used in conjunction with willow spiling and willow stakes.

Plate 6.10
Case study no. 8: regraded bank with Nicospan geotextile protecting the lower shelf and willow stakes at the sloping upper bank (May 1995).

Plates 6.10 and 6.11 show the downstream end of the site, where only Nicospan geotextiles were used to protect the lower bank shelf, with Enkamat geotextiles and willow stakes along the sloping upper bank. Further upstream, willow spiling was used in addition to the Nicospan geotextile to protect the lower bank shelf and no willow stakes were planted higher up the bank (see Plates 6.9 and 6.12). The reason for this variation in design may have been the varying geometry of the banks. Along the lengths where the bank was retained at a relatively steep slope, spiling was used in addition to Nicospan, but no willow stakes were used higher up the bank. The bank angle was reduced significantly where the lower bank shelf was more extensive, thus allowing the bank to accommodate any additional loading that would result from growth of the willows.

Plate 6.11
Case study no. 8: regraded bank with Nicospan geotextile protecting the lower shelf and willow stakes at the sloping upper bank (May 1996).

Plate 6.12
Case study no. 8: regraded bank with Nicospan and spiling protecting the lower shelf (May 1995)

The bank erosion monitoring undertaken at the Upper Wallingford site (Chapter Four) suggested that whilst the rate of erosion was not particularly excessive (approximately 0.15m per year) boat wash was a primary cause of erosion at the toe of the bank and subsequent slumping of the upper bank. Furthermore, desiccation during the summer months led to weakening of the material at the surface of the bank which contributed to its erosion by fluvial entrainment during high flow. Whilst revegetation of the bank was entirely appropriate, the relatively low near-bank velocities experienced at the toe of the bank would suggest that willows could have been installed along the entire length of the site, instead of using solely Nicospan geotextile along the downstream end of the site.

Case study no. 9 **Cleeve Reach: Volume III - Map 19a NGR:461190**

Strategy 6 : structural engineering (gabion mattress / geotextile + riprap)

This site is immediately upstream of case study no. 8 and was also protected by the South Oxfordshire District Council at the beginning of 1995. Whereas conditions at this site were originally similar to the site downstream, here gabion mattresses and riprap were installed (see Plate 6.13). The main aim of the treatment would appear to have been to provide a robust protection which would help to ensure the integrity of the downstream biotechnical engineering solution (case study no. 8). This structural engineering strategy also allowed the slope of the bank to be increased so that there was a more gradual change in bank slope from the biotechnical engineering solution downstream to the steep unprotected bank upstream. The gabion mattresses have remained intact but, whereas the geotextile underlying the riprap protection has also remained intact, by June 1997 the riprap had been removed. The size of the riprap stone was less than about 150mm in diameter, making it vulnerable to removal by hand. It is likely that the rock was stolen. Plate 6.14 shows the revegetated gabion mattress and the exposed geotextile where the riprap has been removed.

Plate 6.13 Case study no. 9: gabion mattress and riprap protection upstream of Wallingford Bridge (taken May 1995)

Plate 6.14
Case study no. 9: exposed geotextile underlay where riprap had been placed (June 1997)

<u>Case study no. 10</u> **Goring Reach: Volume III - Map 20 NGR:459181**

Strategy 5 : biotechnical engineering (geotextile)

This site is along the right bank upstream of Goring Lock and includes the length of bank surveyed at the Goring monitoring site discussed in Chapter Four. The protective measures were installed prior to 1988, but details of the erosion mechanisms and specific causes of erosion are unknown. The Goring Reach is the shortest reach along the non-tidal Thames with only 0.5km between Cleeve and Goring Locks. Observations during the boat wash monitoring exercise described in Chapter Five suggested that there was an element of "jockeying for position" by boats approaching Goring Lock, so that boat wash was likely to be one of the major factors contributing to erosion at this site.

If the consequences of erosion are judged to be 'important', due to the potential risk to the public path along the bank (see Appendix 6.4), the Environment Agency's (1997) framework recommends strategies 2 or 4. Whilst a bioengineering technique such as willow spiling would have been an appropriate solution, a biotechnical engineering solution, Nicospan geotextile, was used to protect the bank (see Plate 6.15).

The majority of the geotextile protection has remained intact for at least 10 years. However, in one particular place, the steel rods used to support the geotextile have been displaced so that they lean towards the channel, and the geotextile has failed (see Plate 6.16). This is either because of undercutting at the toe of the protection, increased loading on the upper bank, or a combination of the two. The water level is relatively high along this reach and the public path becomes flooded during high flows. It is likely that the banks are poorly drained due to the compaction of the soil by pedestrian traffic, and it may be the case that the increased unit weight of the saturated bank has resulted in toppling failure of the steel rods. Furthermore, the length of geotextile in the worst repair is adjacent to a small wooden jetty which probably increases velocities near the bank. At other places, the backfill has been washed out, leaving voids behind the geotextile that can be further eroded (see Plate 6.17).

Plate 6.15
Case study no. 10: Nicospan geotextile along Goring Reach

Plate 6.16
Case study no. 10: displaced support rods and failure of Nicospan geotextile along Goring Reach

Plate 6.17
Case study no. 10:
wash out of backfill
behind Nicospan
geotextile along
Goring Reach

<u>Case study no. 11</u> Mapledurham Reach: Volume III - Map 21 NGR:464177

Strategy 2 & 5: management & biotechnical engineering
(fencing & geotextile + spiling)

Plate 6.18 shows the short length of willow spiling installed at this site in late October 1992. The major cause of erosion here was cattle trampling the banks to access the water's edge, although this was probably exacerbated by boat wash. A geotextile was placed behind the spiling as a filter fabric and the site was enclosed within a sturdy fence to prevent access from livestock (see Plate 6.19).

A public path runs along the edge of the river at this site and, therefore, as in the case of Study no. 10, the consequences of continued erosion could be judged as 'important'. In this case, the Environment Agency's (1997) framework recommends the use of strategies 2 or 4. However, the adjacent land use is rough pasture and there is sufficient space for the public path to be relocated further from the edge of the bank. The consequences of erosion would, therefore, be assessed more realistically as 'moderate', in which case strategies 1, 2 or 3 would be appropriate. Fencing the bank from livestock access would have stopped further bank erosion, but the spiling allowed the bank line to be reinstated and would prevent continued erosion resulting from boat wash.

Plate 6.18 Case study no. 11: willow spiling along Mapledurham Reach

Plate 6.19 Case study no. 11: willow spiling along Mapledurham Reach, with fencing to prevent livestock access

Case study no. 12 **Caversham Reach: Volume III - Map 23 NGR:466176**

Strategy 4 : bioengineering (faggots)

This site is downstream of Mapledurham Lock and opposite Mapledurham Weir. Plate 6.20 is a downstream view of the site showing the erosion of the bank downstream of concrete bagwork.

Plate 6.20 Case study no. 12: erosion downstream of Mapledurham Lock prior to bank protection

The author participated in the design team for this project in the way described by Brookes (1995), and assessed the major causes of erosion here to be high flows from the weir opposite, and boat wash. The adjacent land use is rough pasture, although there was no evidence of livestock grazing. Judging the consequences of erosion as 'moderate', the Environment Agency's (1997) framework recommends the use of strategies 1, 2, 3 or 4. Formation of a spending beach at the level of the water surface, coupled with the stability of the clayey bank material below the level of the water surface suggested that undercutting at the toe of the bank (i.e. above the clayey material) was primarily the result of boat wash. In this respect the site is similar to the Lower Wallingford monitoring site (Chapter Four). Erosion of the upper bank cliff probably resulted from a combination of undercutting, weakening of the unvegetated face of the bank during summer months, and removal of material by high flows from the weir opposite.

Strategy 1, allowed natural adjustment, was proposed by the author but the riparian owner would not accept further loss of land through continued bank erosion. The option to regrade the slope of the upper bank to a stepped profile and replant the bank for longer-term stability was also proposed by the author but, again, agreement could not be secured from the landowner. Consequently, faggots were installed to protect the toe of the bank from continued erosion by boat wash and also, to some extent, from high flows from the weir (see Plate 6.21). In developing this design, it was recognised that, without protecting the steep upper bank, the high flows from the weir may continue to erode the upper bank. However, with adequate toe protection, rate of upper bank retreat would be expected to decline with time, and the bank would eventually stabilise and revegetate.

Plate 6.21 Case study no. 12: faggot bank protection downstream of Mapledurham Lock

<u>Case study no. 13</u> Marlow Reach: Volume III - Map 30 NGR:484184

Strategy 5 : biotechnical engineering (geotextiles)

Nicospan geotextile was installed at this site some time prior to the 1992 River Thames Bank Survey (Volume II). The specific mechanisms of failure at this site are not known but it is similar to the St. John's monitoring site and Case study no. 1 reported above, in that cattle graze the adjacent land and access the water's edge in places. A public path runs along the edge of the river, but there are no fences to restrict the width or the alignment of the path. Judging the consequences of erosion here as 'moderate', the Environment Agency's (1997) framework recommends the use of strategies 1, 2 or 3.

Plate 6.22 shows where a length of the Nicospan geotextile has failed, leaving behind the vertical steel rods used to secure the geotextile. This particular length of bank is accessed by cattle and protection along other, similarly accessible lengths also failed. Where the bank is not accessible to livestock, the Nicospan geotextile has remained intact. A more appropriate strategy would have been either to allow natural adjustment of the bank, or fence off the bank to prevent livestock poaching. Similarly to Case study no. 1, in order to maintain access to the water's edge for livestock to drink, a sacrificial length of bank would be required at which erosion was allowed to continue. Alternatively, to prevent further erosion, use could be made of a biotechnical engineering technique such as open cell revetment, or a structural engineering solution such as stone revetment.

Plate 6.22
Case study no. 13: failed Nicospan geotextile along Marlow Reach

Case study no. 14 **Marlow Reach: Volume III - Map 30 NGR:484185**

Strategy 4 : bioengineering (spiling)

Plate 6.23 shows erosion of the bank along Marlow Reach, adjacent to an unvegetated public path which runs parallel to the river. The major causes of erosion were identified as boat wash and pedestrian access (Browne, 1993). The consequences of erosion here could be judged as 'moderate' because there is sufficient space along the river corridor to accommodate realignment of the footpath if erosion continued. In this case, the Environment Agency's (1997) framework recommends the use of strategies 1, 2 or 3. Whereas strategies 1, 2 and 3 could have been adopted, the willow spiling that was used provided adequate protection from boat wash, allowed the bankline to be reinstated and provided a more diverse habitat along the bank (see Plate 6.24).

Plate 6.23 Case study no. 14: bank erosion at Marlow Reach.

Plate 6.24 Case study no. 14: willow spiling bank protection along Marlow Reach.

Case study no. 15 Cookham Reach: Volume III - Map 31 NGR:486185

Strategy 6 : structural engineering (sheet piling + riprap)

This site is opposite an island downstream of Marlow Lock, where flow impinges against the bank because of the geometry of the channel. The edge of the bank was initially approximately 3m away from fenced grazing land, where the bank adjacent to a public footpath had been eroded away to a cliff face approximately 2m high (see Plate 6.25).

Plate 6.25 Case study no. 15: steep eroding cliff face along Cookham Reach

Judging the consequences of the slab failure to be 'important' and the major causes of erosion to be river processes (see Appendix 6.4), the Environment Agency's (1997) framework recommends strategies 4, 5 and 6. Sheet piling with a wooden capping beam was used to protect the lower bank to just above the standard water level and riprap was used to protect higher up the bank (see Plate 6.26). Willow plantings in hessian bags were placed within the riprap to accelerate revegetation (see Plate 6.27).

Plate 6.26
Case study no. 15: wood-capped sheet piling and riprap protection along Cookham Reach, after installation in spring 1995

Plate 6.27
Case study no. 15: revegetation of riprap protection along Cookham Reach (June 1997)

The author participated as the geomorphology specialist in the design of this project in the way described by Brookes (1995). In this capacity, the author proposed the option of realigning the footpath by moving the fence further away from the channel, but this option was not pursued with the landowner. The author also identified the option to regrade the bank angle to a stepped profile and use a bioengineering technique to stabilise the bank but, without realigning the adjacent fence, there was insufficient space to regrade the bank and maintain the public path. Regrading the bank angle by buttressing the toe of the bank with gabion baskets to form a lower bank terrace and planting of willows above, was not acceptable to the Environment Agency's navigation function because of the risk of damage to craft from underwater obstructions.

This bank protection project was undertaken as part of a larger project to construct new mooring facilities downstream of Marlow Lock. This reach of the River Thames is popular for angling and, in recognition of the impacts on angling that would result from the new mooring facilities, a number of mitigation measures were incorporated into the project. These included the removal of several lengths of old, redundant sheet piling and the construction of a fishing bay. The fishing bay was excavated along the inside of a bend and enclosed with coir fibre rolls planted with reeds (see Plate 6.28).

Plate 6.28 Case study no. 15: fishing bay excavated along Cookham Reach as an environmental enhancement

<u>Case study no. 16</u> Cookham Reach: Volume III - Map 31 NGR:489185

Strategy 4 : bioengineering (spiling)

This site is at the upstream end of Cookham Lock Cut, along the right bank of Sashes Island. Originally, the bank was vertical and approximately 1.2m high (see Plate 6.29). The major factors contributing to erosion here were identified as access for fishing and boat wash along the lock cut. In addition, the bank upstream is protected with a length of sheet piling that will tend to concentrate high velocity flow near the unprotected bank downstream.

Plate 6.29
Case study no. 16: bank erosion along Cookham Lock Cut

A public path runs along the top of the bank. Furthermore, continued erosion of the bank would eventually result in a breach of the peninsula of land that supports Cookham Weir. Such a breach would cause flow to bypass the weir, with significant implications for flooding downstream.

The author participated as the geomorphology specialist in the design team for this project in the way described by Brookes (1995). Whereas the flood defence risks associated with the bank erosion were originally considered potentially 'severe', the author's assessment of the causes of erosion and recognition of the relatively low flow velocities along the lock cut, led the design engineers to re-evaluate these risks as 'important'. The formation of a spending beach here at the level of the water surface, similar to those observed at the Lower Wallingford and Chertsey monitoring sites, suggested that protection of the toe of the bank with a bioengineering technique such as willow spiling would prevent continued erosion from boat wash.

In order to accommodate access for anglers, the bank was regraded to stepped profile and willow spiling was installed to protect the toe and shelf (see Plate 6.30). As a further enhancement measure, flint gravels were placed at the toe of the bank to provide additional fish spawning habitat.

Plate 6.30
Case study no. 16:
willow spiling along
Cookham Lock Cut

<u>Case study no. 17</u> **Boulter's Reach: Volume III - Map 32 NGR:489185**

Strategy 6 : structural engineering (sheet piling + gabion baskets)

This site is directly opposite Cookham Weir and on the other side of Sashes Island to Case study no. 16, described above. The eroding bank was downstream of a length of intact sheet piling where the displaced concrete bagwork is shown in Plate 6.31. Continued erosion of the bank and a resulting breach across the Island would lead to a similar flood risk to that described for Case study no. 16. However, flow opposite the weir would reach significantly higher velocities than along the lock cut and, therefore, the consequences of continued erosion were considered 'severe'.

Plate 6.31
Case study no. 17: Bank erosion opposite Cookham Weir

The Environment Agency's (1997) framework recommends strategies 5 or 6 where erosion consequences are 'severe' and where the strategy is required to address flood defence issues. Furthermore, the high banks and relatively steep slope, along with the high velocity environment, would suggest that structural engineering techniques were the most appropriate solutions.

The author participated as the geomorphology specialist in the design team for this project in the way described by Brookes (1995). Consideration of the relatively high turbulence expected downstream of the weir led the author to propose an option to regrade and the bank to a stepped profile using gabion baskets as protection. However, the limited space available and the detrimental impact on the mature vegetation at the top of the bank meant that this option was not pursued. Alternatively, sheet piling was installed to protect the toe of the bank, with gabion baskets above the piling to protect higher up the bank and prevent high flows from the weir causing erosion behind the piles (see Plate 6.32). The site was also seeded with a wild-flower mix and has since revegetated sufficiently to mask the visual appearance of the hard engineering structure (see Plate 6.33).

Plate 6.32
Case study no. 17: sheet piling and gabion baskets opposite Cookham Weir (June 1995, after construction)

Plate 6.33
Case study no. 17: revegetation of gabion baskets 2 years after installation

Case study no. 18 Egham Reach: Volume III - Map 37 NGR:499174

Strategies 4/6 : bioengineering/structural engineering (gabions/faggots)

This site is along the right bank of Old Windsor Lock Island and immediately downstream of a side-sluice off the main channel. The major cause of erosion was identified as high flow velocities from the sluice exacerbated by the upstream sheet piling (see Plate 6.34), although no specific failure mechanism was identified.

The consequences of erosion at this site could be judged as 'important' because of the potential risk to the adjacent sluice structure. Hence, Environment Agency's (1997) framework recommends the use of strategies 2, 4, 5 or 6. However, with a bank height of approximately 3m, a slope of 60° to 80° and high flow velocities, the framework suggests that the bioengineering techniques are inappropriate.

The author participated as the geomorphology specialist in the design team for this project and proposed an option to protect the lower bank using a structural engineering solution such as gabions below the water level to create a step at the toe of the bank. Such a step would act as a buttress and protect the toe from scour by high velocities. However, a mooring platform in front of the bank meant that there was insufficient room to encroach into the channel with protective structures, and there was also insufficient space on the lock island to regrade the upper bank to a similarly stepped profile. Furthermore, the use of this location for mooring meant that underwater structures would have posed a potential hazard to boats.

Consequently, gabion baskets were installed at the upstream end of the site adjacent to the existing sheet piling (see Plate 6.34), and willow faggots were installed downstream where erosion posed less of a risk to the sluice (see Plate 6.35).

Plate 6.34
Case study no. 18: gabion baskets installed along Egham Reach

Plate 6.35
Case study no. 18: willow faggots installed along Egham Reach

<u>Case study no. 19</u> Egham Reach: Volume III - Map 37 NGR:500172

Strategy 6 : structural engineering (gabion baskets)

This site is along the inside of a bend upstream of Egham Lock and was protected with gabion baskets some time prior to 1992 (see Plate 6.36). The characteristics of the bank prior to installation of the protection are unknown. Likewise, the specific failure mechanisms are also unknown but the location is particularly popular for navigation and general amenity hence, the major causes of erosion were likely to be boat wash and other recreational activities.

A public path runs along the edge of the river and, whilst the adjacent land use is clearly valuable as a recreational asset, there are no constraints to prohibit the realignment of the path further away from the river. The consequences of erosion are, therefore, considered to be 'moderate'. In this case, the Environment Agency's (1997) framework suggests that only strategies 1, 2 or 3 would be appropriate if retaining the existing alignment of the public path was not necessary, but strategy 4 should be considered if the path was to be retained along its existing alignment.

This site is along the inside of a bend, and is, therefore, not subject to significant fluvial attack during high flows. It is, therefore, likely that a biotechnical solution such as willows could have been used to protect the bank from boat wash if prevention of continued erosion was the overriding objective. Alternatively, a more appropriate strategy might have been to allow the natural adjustment of the bank.

Plate 6.36
Case study no. 19: gabion baskets installed along Egham Reach

<u>Case study no. 20</u> Shepperton Reach: Volume III - Map 40 NGR:505166

Strategy 6 : structural engineering (gabions)

This site is along the outer bank of a meander bend downstream of Chertsey Lock. The condition of the site and the specific erosion mechanisms prior to works are unknown. However, the channel geometry would suggest that erosion was primarily due to high velocities along the outside of the bend, probably exacerbated by hard bank protection upstream. The adjacent land has as an informal picnic area and a public path approximately 75m from the edge of the river. Hence, the consequences of erosion can be considered 'moderate'. Assuming that either cantilever or slab failures were the main failure mechanism, the Environment Agency's (1997) framework recommends the use of strategies 1 or 4.

Gabion baskets were installed to protect the bank in the late 1980s (see Plate 6.37). It is not known if other strategies were considered, but alternative approaches could have been to allow the natural adjustment of the bank, or to regrade the bank to a stepped profile and use a bioengineering protection technique. Regrading the bank angle would have reduced the near-bank velocities generated at the outside of the bend by secondary currents. Furthermore, stabilising a stepped profile would have facilitated access to the river where there is now a high, vertical bank.

Plate 6.37
Case study no. 20: gabion baskets installed along Shepperton Reach

Case study no. 21 **Teddington Reach: Volume III - Map 43 NGR:516171**

Strategy 4/6 : bioengineering/structural engineering (riprap/faggots)

This site is along the right bank of Teddington Lock Island, immediately downstream of Teddington Weir. The site is, therefore, not strictly within the Teddington Reach, but is just within the tidal limits of the River Thames. Plate 6.38 shows the bank along which the erosion problem was identified, and Plate 6.39 shows the scour behind the sheet piling which supports the upstream weir.

Plate 6.38 Case study no. 21: downstream of Teddington Weir prior to bank protection

Plate 6.39 Case study no. 21: scour behind sheet piling downstream of Teddington Weir

The author participated as the geomorphology specialist in the design team for this project and identified the major cause of erosion as the high velocity flow from the weir scouring the reach where the bank was unprotected and most vulnerable, immediately downstream of the sheet piling. The consequences of erosion could be judged as 'important' due to the potential risk to the weir structure and, as such, the Environment Agency's (1997) framework recommends the use of strategies 2, 4, 5 or 6.

High flow velocities downstream of the weir would suggest that a structural engineering technique would be the most appropriate solution to prevent the localised erosion immediately downstream of the piling. Riprap was, in fact, used to protect the bank at the end of the sheet piling (see Plate 6.40).

Plate 6.40 Case study no. 21: riprap installed to prevent scour downstream of sheet piling, with Teddington Weir in the background

Faggots were installed above the level of the riprap to provide protection to the upper bank and help dissipate the energy from high flows. Further along the site and downstream from the influence of the weir, erosion was considered to pose less risk to the adjacent structure and faggots were again used to protect the bank and dissipate energy (see Plate 6.41). As an additional enhancement measure, a footpath was formalised along the top of the bank.

Plate 6.41 Case study no. 21: faggots installed downstream of Teddington Weir

6.4 Performance review of erosion control case studies

To assess the performance of the alternative erosion control case studies outlined above, each has been reviewed against the five criteria listed at the beginning of Section 6.3 on page 169-70 (see Table 6.3).

The review was undertaken against each criterion by evaluating the evidence listed in Table 6.3. For the case studies where the author participated directly in the design of the solution, detailed knowledge was available regarding the reasoning responsible for selection of the solution employed and the design of mitigation and enhancement measures. Five of the case studies recorded used two techniques to address the bank erosion (case study nos. 3, 5, 11, 18 and 21). These case studies have been separated into the component techniques in Appendices 6.4 and 6.5 to produce a total of 26 strategies adopted in the 21 case studies recorded.

Table 6.3 Source of evidence to evaluate the performance of case studies

Performance criteria		Source of evidence
i)	Strategy: compliance with the Environment Agency's (1997) recommended strategy	Retrospective review against the Environment Agency's (1997) framework guidance
ii)	Integrity: erosion control as expected (i.e., no failure)	Site visit to observe evidence of failure
iii)	Improvements to design: if additional measures would have improved the performance of the solution	Retrospective review against the Environment Agency's (1997) framework guidance
iv)	Mitigation: if environmental impacts have been mitigated	Review of environmental assessment documentation and interview with land drainage authority officers
v)	Enhancement: if environmental enhancements have been included	

Assessment of the compliance of the erosion control strategies adopted in the case studies against the strategies recommended by the Environment Agency's (1997) framework was undertaken by determining whether:

- the strategy adopted was the optimum strategy recommended using the framework, or
- the strategy adopted was one of the strategies recommended using the framework, but not the optimum strategy, or
- the strategy adopted was not one of the strategies recommended using the framework.

In this assessment, the optimum (most preferable) strategy is that with the lowest number in Table 6.1. The strategy adopted for each case study is ranked in Appendix 6.5 according to its performance against criterion (i), i.e. compliance with the Environment Agency's (1997) recommendations. Where the strategy adopted was the optimum of those recommended, it has been given a performance ranking of 'high'. Where the adopted strategy was one of those recommended, but not the optimum strategy, it has been given a performance ranking of 'medium', and where the adopted strategy was not recommended, the case study has been given a performance ranking of 'low'.

Figure 6.1 compares the strategies adopted in the case studies with the optimum strategies recommended using the Environment Agency's (1997) framework (see Appendix 6.5).

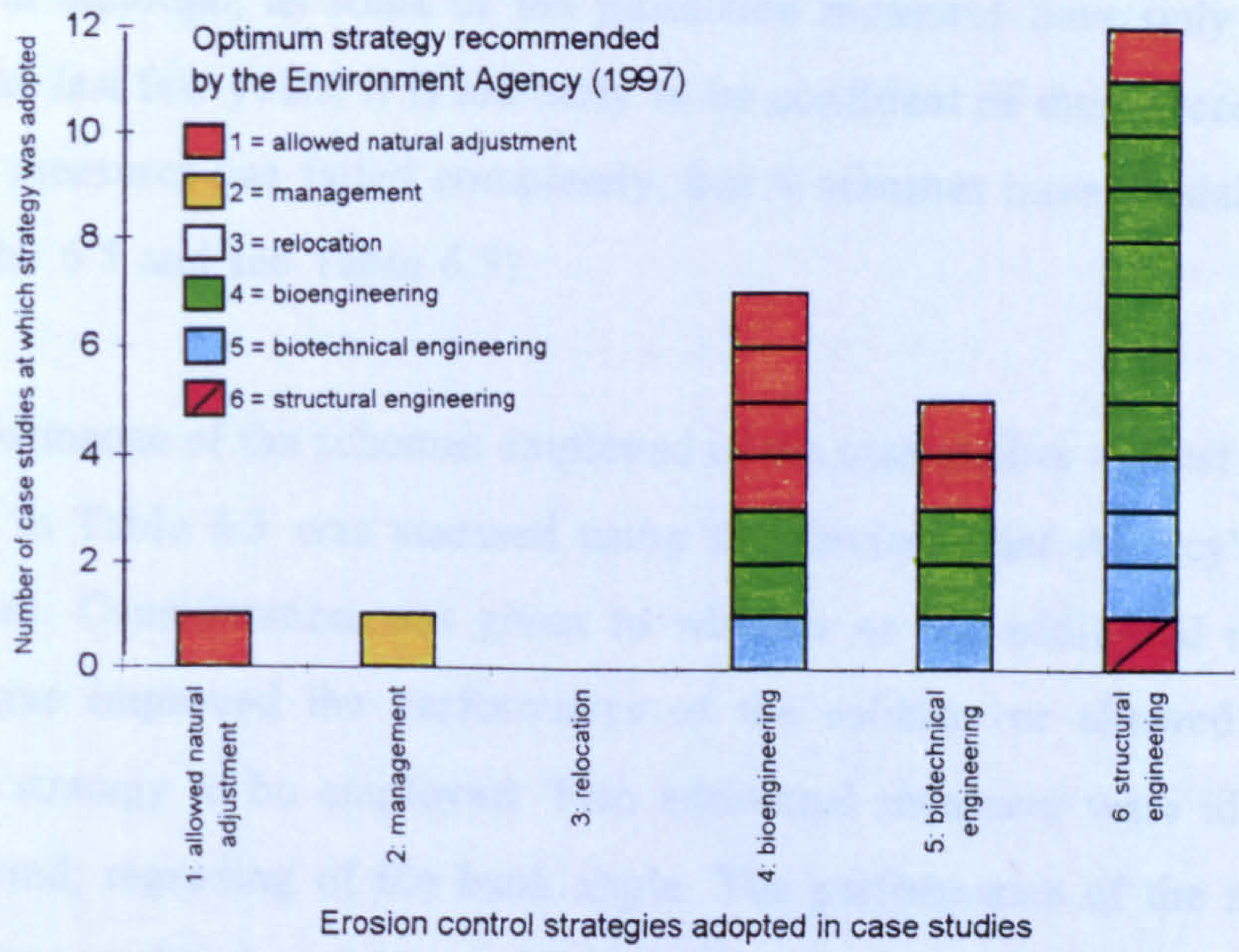


Figure 6.1 Comparison between adopted erosion control strategies and those recommended by the Environment Agency (1997)

The horizontal axis in Figure 6.1 categorises the various strategies that were adopted in practice, while the colours indicate the strategies that were recommended using the Environment Agency's (1997) framework. The graph clearly shows that, in the majority of cases, the strategy adopted to address the erosion problem was inappropriate. Only six strategies adopted (23%) were the optimum strategies recommended by the Environment Agency's (1997) framework. A further six adopted strategies (23%) were recommended but were not the optimum strategies that could have been implemented. The remaining 14 adopted strategies (54%) were not recommended by the Environment Agency's (1997) framework (see Table 6.5).

The performance of the erosion control strategies against the second criterion in Table 6.3 was assessed by observing the condition of the erosion control measures. Performance against criterion (ii) has been ranked as 'high" if the measures have remained intact and prevented bank erosion, 'medium' if the measures have partially failed, or 'low' if the scheme has completely failed. The majority of the strategies adopted (81%) have so far been completely successful although, as some of the protection measures have only installed within the last few years, it is too early to be confident of their success. Only 1 set of measures has failed completely, but 4 schemes have partially failed (Appendix 6.5 and see Table 6.5).

The performance of the schemes employed in the case studies against the third criterion in Table 6.3 was assessed using the Environment Agency's (1997) framework. Consideration was given to whether or not additional measures would have improved the performance of the solution or allowed a more sensitive strategy to be employed. Two additional measures were identified: fencing, and; regrading of the bank angle. The performance of the solutions used in case studies 1 and 13 would have been improved if fencing had been used to prevent livestock from destroying the protective measures. More sensitive techniques could also have been adopted in a further 7 case studies had the slope of the bank been reduced by regrading (see Appendix 6.5). Performance against this criterion has been ranked as 'low' and 'medium' if fencing or regrading, respectively, could have improved the solution. The rationale behind this ranking is that the exclusion of fencing from the design is considered a failure of the design, whilst not regrading the bank is more a lack comprehensive option evaluation and imaginative problem solving. Performance had been ranked as 'high' if no additional measures were identified (see Appendix 6.5 and Table 6.5).

Performance of the case studies against criterion (iv), mitigation of environmental impacts, has been evaluated by first considering the severity of the impacts resulting from the solution adopted, and then by considering any additional measures incorporated into the solution to reduce those impacts.

In addition to the visual impact, the main long-term impact resulting from bank protection is the reduced ecological value of the river margins. Clearly, different materials will produce different impacts on the marginal ecology necessitating different mitigation measures. Table 6.4 lists the criteria used to determine the severity of impacts and the corresponding mitigation measures, which are considered 'low', 'medium' and 'high' performance with respect to criterion (iv).

Table 6.4 Severity of impacts and requirements for mitigation measures

Strategy	Relative severity of impact	Additional mitigation measures	Performance ranking for criterion (iv)
1, 2 and 3	No impact	N/A	N/A
4	Low	Renaturalisation	High
		Yes/No	High
5: except open cell concrete	Low	Renaturalisation	High
		Yes	High
		No	Medium
5: open cell concrete; 6: gabions & riprap	Medium	Renaturalisation	High
		Yes	High
		No	Medium
6: except gabions & riprap	High	Renaturalisation	High
		Yes	Medium
		No	Low

The criteria used in Table 6.4 are generally based on the sustainability hierarchy that underpins the Environment Agency's (1997) framework, so that impacts resulting from bioengineering strategies are considered 'low'. Impacts from the majority of biotechnical engineering solutions are also considered to be relatively 'low'. The exception to this rule is the impact of open cell concrete which is considered 'medium' due to the resulting unnatural interface between the bank and river. Gabions and riprap are also considered to have 'medium' impact because they provide a more natural interface between that bank and river than the other structural engineering solutions, which are considered to have a 'high' impact.

To evaluate how adequately mitigation measures reduced or compensated impacts, a further set of criteria were established that also hinge on sustainability principles. Table 6.4 shows these criteria and how the performance ranking was derived. The impacts of each strategy were considered in the light of three mitigation scenarios. The scenarios are listed as additional mitigation measures in Table 6.4 and comprise (1) renaturalisation of river bank, whereby impacts on the river corridor are compensated by improving the corridor elsewhere, (2) where some kind of additional mitigation measures have been incorporated into the design to reduce impacts, and (3) where no additional mitigation measures have been incorporated.

The performance ranking against criterion (iv) was then derived by comparing the impacts of the strategies and mitigation measures adopted in the case studies with the scenarios listed in Table 6.4. For example, if sheet piling (strategy 6) were used to protect a bank, a performance ranking of 'high' could only be achieved if a river bank elsewhere were renaturalised as compensation. On the other hand, because of the relatively low severity of impact, and the fact that bioengineering techniques use vegetation as opposed to unnatural materials, mitigation of this strategy ranks a performance of 'high' even without additional mitigation measures.

The performance of the case studies judged against criterion (v) in Table 6.3 was evaluated by determining the level of environmental enhancement resulting from the solution adopted. If, for example, the solution involved the replacement of failed sheet piling with a bioengineering solution, then the overall result would be an improvement to the existing environment and warrant a performance ranking of 'high'. No such situations were recorded in the case studies because the renaturalisation undertaken as part of case study 15 was in compensation for the use of sheet piling. The only enhancements carried out were at case study 15 which included the creation of a fishing bay with reed planting, and case study 16 which included recharge of the gravel beach. Consequently, the performance of these two cases was ranked 'medium', compared to performance of the remaining case studies which was ranked 'low' (see Appendix 6.5 and Table 6.5).

The performance of the case studies judged against the criteria in Table 6.3 is shown in Table 6.5 and illustrated in Figure 6.2. Whilst this analysis has been based on only a limited number of cases, it does provide useful management information on the strengths and weaknesses of existing practices. Figure 6.2 clearly shows that performance has been particularly poor in terms of selecting the most appropriate erosion control strategies and incorporating environmental enhancements. Conversely, performance is relatively good with regard to designing solutions that control erosion and mitigating impacts. However, if solutions tend to be over-designed in the first instance, as suggested by Figure 6.1, then it is not surprising that performance is 'high' in terms of structural integrity and erosion control. Furthermore, whilst performance in terms of adequate mitigation measures may well be 'medium' or 'high', again, the over-design of solutions in the first instance means that impacts will tend to be higher and therefore require greater measures to mitigate.

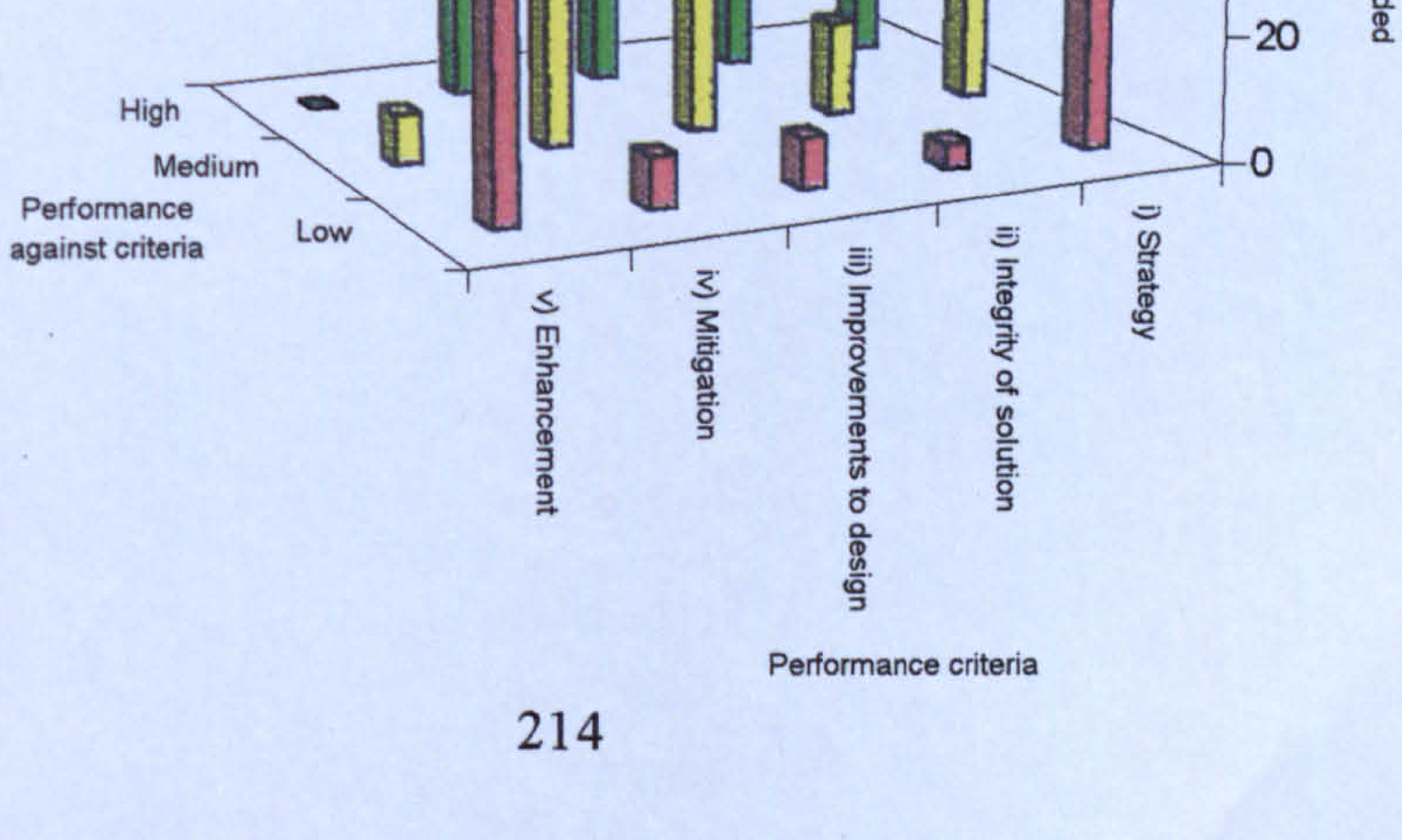
This analysis suggests that, if existing performance continues, there will be environmental deterioration. Furthermore, resources are being invested to deliver over-engineered solutions, which then require further investment to mitigate impacts. In these instances a 'softer' engineering solution may incur less capital costs and require less mitigation. If practice is to improve, consideration should be given to providing more prescriptive guidance on various aspects of erosion management. In particular, guidance is required in relation to two key steps. The first step requiring stronger guidance is the selection of the most appropriate strategy. At present, the Environment Agency's (1997) guidance provides only a framework through which to enter a potentially subjective assessment of the severity of the consequences of erosion. The second step requiring better guidance is in specifying the requirements for mitigation and enhancement. Whilst performance against criterion (iv), mitigation, was ranked as 'high' for 46% of the case studies, only 17% included specific measures designed to mitigate impacts, the remainder being ranked 'high' because the strategies adopted had relatively 'low' impacts. Chapter Seven provides more prescriptive guidance for managing bank erosion problems on the River Thames which addresses these requirements.

Table 6.5 Performance summary of erosion control case studies on the River Thames

Performance criteria (see Table 6.3)		Numbers and percentages of cases ranked according to performance					
		HIGH		MEDIUM		LOW	
		No.	%	No.	%	No.	%
i)	Strategy (n = 26)	6	23	6	23	14	54
ii)	Integrity (n = 26	21	81	4	15	1	4
iii)	Improvements (n = 26)	17	65	7	27	2	8
iv)	Mitigation (n = 24)	11	46	11	46	2	8
v)	Enhancements (n = 26)	0	0	2	8	24	92

Note: n = number of erosion control techniques included in sample:
2 techniques involved no works to the bank, therefore, resulted in no impacts to mitigate.

Figure 6.2 Performance of case studies against criteria (i) to (v)



CHAPTER SEVEN

THE RIVER THAMES
BANK EROSION MANAGEMENT STRATEGY

7.1 Introduction

This chapter draws on the findings presented in the previous chapters to develop a framework through which to achieve the research objectives listed in Chapter One. The chapter aims to provide a strategy through which to manage bank erosion along the non-tidal, navigable River Thames whilst optimising performance in terms of environmental improvement. As the land drainage and navigation authority for the non-tidal, navigable River Thames, the Environment Agency (Thames Region) is the key player in the implementation of any such strategy, hence, the framework has been developed primarily as a tool for the Environment Agency to contribute towards sustainable river management.

Section 7.2 reviews the momentum behind the development of the strategy, drawing on the most relevant legislation and policy guidance, and various initiatives designed to contribute towards achieving sustainable development.

Section 7.3 draws together the information presented in previous chapters to develop a strategy for managing bank erosion on the River Thames. The structure of the framework is described as a transferable implementation tool to complement the Environment Agency's approach to environmental impact assessment and management, and its guidelines for the assessment and management of bank erosion (Environment Agency, 1997). The chapter ends by reviewing the contribution of this research to bank erosion management along the non-tidal, navigable River Thames.

7.2 Initiatives contributing towards sustainable development

The Environment Agency is the land drainage authority for the non-tidal, navigable River Thames and has a duty to contribute to the attainment of sustainable development throughout England and Wales. Under the 1991 Water Resources Act and 1995 Environment Act (HMSO, 1991; 1995) the Environment Agency has a general duty to enhance natural beauty, conserve flora and fauna and consider costs and benefits in all its activities. To this end, the Environment Agency has developed and adopted various tools including Local Environment Agency Planning, LEAP (developed from Catchment Management Planning). The LEAP process provides a mechanism through which the Environment Agency consults with stakeholders, evaluates environmental issues and acts to address various issues within the plan area (see Figure 7.1).

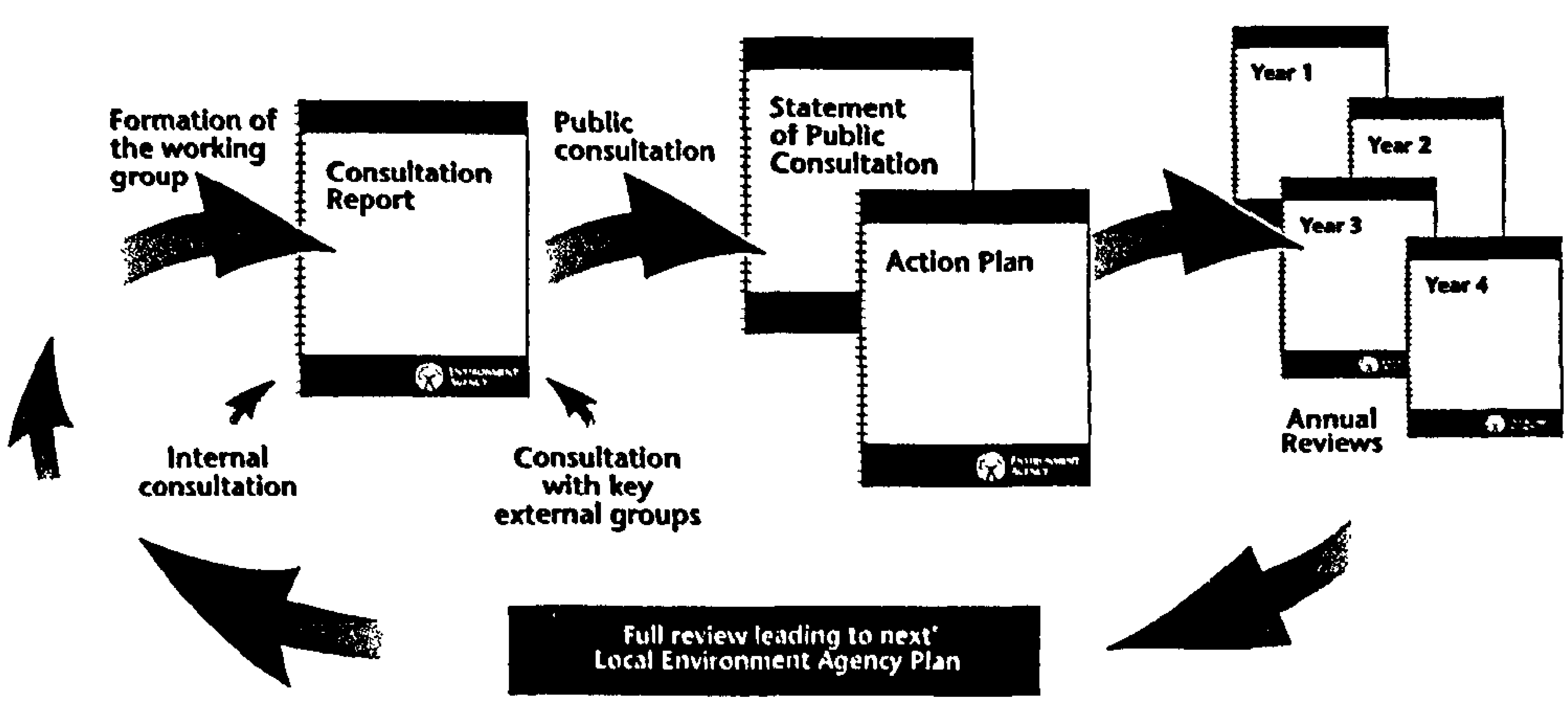


Figure 7.1 The Local Environment Agency Planning Process (Environment Agency, 1998h)

Whilst the approach adopted by LEAPs is well established (Woolhouse, 1994), the Environment Agency has more recently prepared *An Environmental Strategy for the Millennium and Beyond* (Environment Agency, undated b) which describes the Environment Agency's aims and its approach to managing the environment. A greater emphasis is now being placed on reporting the Environment Agency's performance in terms of environmental improvement with 'State of the Environment Reporting' a key mechanism through which to measure improvement (Environment Agency, 1998b). Due to the wide ranging duties of the Environment Agency (HMSO, 1991; 1995), and the need for such a strategy to be sufficiently non-specific to be generally applicable to England and Wales, implementation of the *Environmental Strategy* could, in practice, lead to no particular changes in the activities undertaken by the Environment Agency. However, the Environment Agency has recently introduced new guidelines for LEAPs in support of the *Environmental Strategy* which aim to prioritise activities according to environmental consequences. In this way, issues presenting a high risk to the environment, or actions resulting in significant environmental improvement, are given a high priority.

This new *Version 3 LEAP Guidance* (Environment Agency, 1998c) adopts a 'pressure-state-response' approach which requires evaluation of the 'pressures' on the environment and the resulting strain on the environment in terms of the 'state' of the environment. Analysis of these causes and consequences allows thorough evaluation of the success of alternative strategies (responses) designed to address the strain. Such responses may address the strain on the environment directly, for example, by undertaking works to alleviate a flooding problem, or indirectly via the 'pressure', for example, by reducing development within the floodplain.

Whilst the strain on the environment can be simply defined as the deficit between the existing 'state' of the environment and the required 'state' of the environment, information is not always readily available to express the strain and thus, monitor environmental improvement (Environment Agency, 1998b). Moreover, given the inadequate situation of empirical evidence regarding the impact of human activity on the environment, technical experts can rarely provide policy-makers with unambiguous advice about trade-offs among competing long-term goals (World Bank, 1995). Without such information readily available there is thus, little opportunity to formulate effective management strategies and develop realistic and cost-effective targets for improvement.

In recognition of the importance of information to environmental management, the Environment Agency has adopted various indicators of environmental quality that can be interpreted by stakeholders and that are relatively easily or routinely measured. The use of indicators of environmental quality was recently adopted in a land-use planning strategy, *Thames Environment 21*, developed specifically for Thames Region (Environment Agency, 1998d). *Thames Environment 21* employs a framework of sustainability principles to identify key environmental indicators that could be used to measure the 'pressures' on the environment, the 'state' of the environment and the 'response' of the Environment Agency (and other stakeholders) to the environmental strain. Six sustainability principles are used to encompass the Environment Agency's aims in Thames Region (Table 7.1).

Table 7.1 Six Sustainability Principles in Thames Region (Environment Agency, 1998d)

Thames Region Sustainability Principles	
1	To manage groundwater and surface-water resources to achieve the right balance between the needs of society and of the natural environment.
2	To manage floodplains and flood risk for the benefit of people and the natural environment and for the protection of property.
3	To maintain and where possible improve the quality of air, land and water through the prevention and control of pollution, and by applying the 'polluter pays' principle.
4	To achieve reductions in waste through minimisation, re-use, recycling and improve standards of handling and disposal.
5	To conserve and enhance the natural, cultural and historic value of river corridors, their landscapes and biodiversity.
6	To retain, improve and promote water and waterside land for the purposes of public access and enjoyment, navigation and appropriate recreational use.

The *Thames Environment 21* strategy lists various environmental indicators that could be used within the 'pressure-state-response' framework. The strategy also describes mitigation and enhancement opportunities and the Environment Agency's commitment to each of the sustainability principles. Whilst the Environment Agency's duties are wide-ranging, sustainability principles 5 and

6, listed in Table 7.1, are specifically relevant to the River Thames and the erosion management strategy presented in this chapter. Relevant indicators, mitigation and enhancement opportunities from these two sustainability principles are listed in Table 7.2, together with the relevant commitments made by the Environment Agency.

Table 7.2 Indicators, mitigation and enhancement opportunities and Environment Agency commitments under sustainability principles 5 and 6 (Environment Agency, 1998d)

<table>
<tr><td colspan="2">Sustainability principle 5: conserve and enhance the natural and historic value of river corridors, their landscapes and biodiversity</td></tr>
<tr><td colspan="2">Potential environmental indicators:
- State: Length of natural river bank</td></tr>
<tr><td colspan="2">Mitigation and enhancement opportunities:
- Re-shaping or improvement of river channels or banks</td></tr>
<tr><td colspan="2">Environment Agency commitment:</td></tr>
<tr><td>- Priorities and targets:</td><td>To promote and secure funding for river restoration and wetland rehabilitation
To understand the importance of local biodiversity in the context of national and international objectives</td></tr>
<tr><td>- Research and development:</td><td>Develop methodology to evaluate environmental impact
Develop cost-effective management strategies and techniques which secure conservation and biodiversity objectives</td></tr>
<tr><td colspan="2">Sustainability principle 6: retain, improve and promote water and waterside land for the purposes of public access and enjoyment, navigation and appropriate recreational use</td></tr>
<tr><td colspan="2">Potential environmental indicators:
- Pressure: Length of river corridor subject to overuse from recreation
- State: Length of river bank with public access
- Response: Length of river corridor enhanced</td></tr>
<tr><td colspan="2">Mitigation and enhancement opportunities:
- Improved physical or visual access to watercourses or water-bodies
- Creation of new public riverside footpaths and open spaces
- Delivery of improvements in environmental quality benefitting recreation</td></tr>
<tr><td colspan="2">Environment Agency commitment:</td></tr>
<tr><td>- Priorities and targets</td><td>Net increase in safe access to waterside areas</td></tr>
<tr><td>- Research and development</td><td>Develop measures to mitigate the impact of recreation on the environment where appropriate
Identify best practice recreational management techniques</td></tr>
</table>

Mindful of the broad principles of sustainability, the Environment Agency has recently developed various policy initiatives designed to improve environmental performance. One of these initiatives is the Environment Agency's *Environmental Policy*, aimed at improving the overall environmental performance of the organisation through sound management practices (Figure 7.2). Whilst the Environment Agency is not accredited with any environmental quality standards such as ISO 14001 (BSI, 1996), the *Environmental Policy* demonstrates a sufficient level of organisational commitment through which to design and implement performance monitoring systems worthy of accreditation.

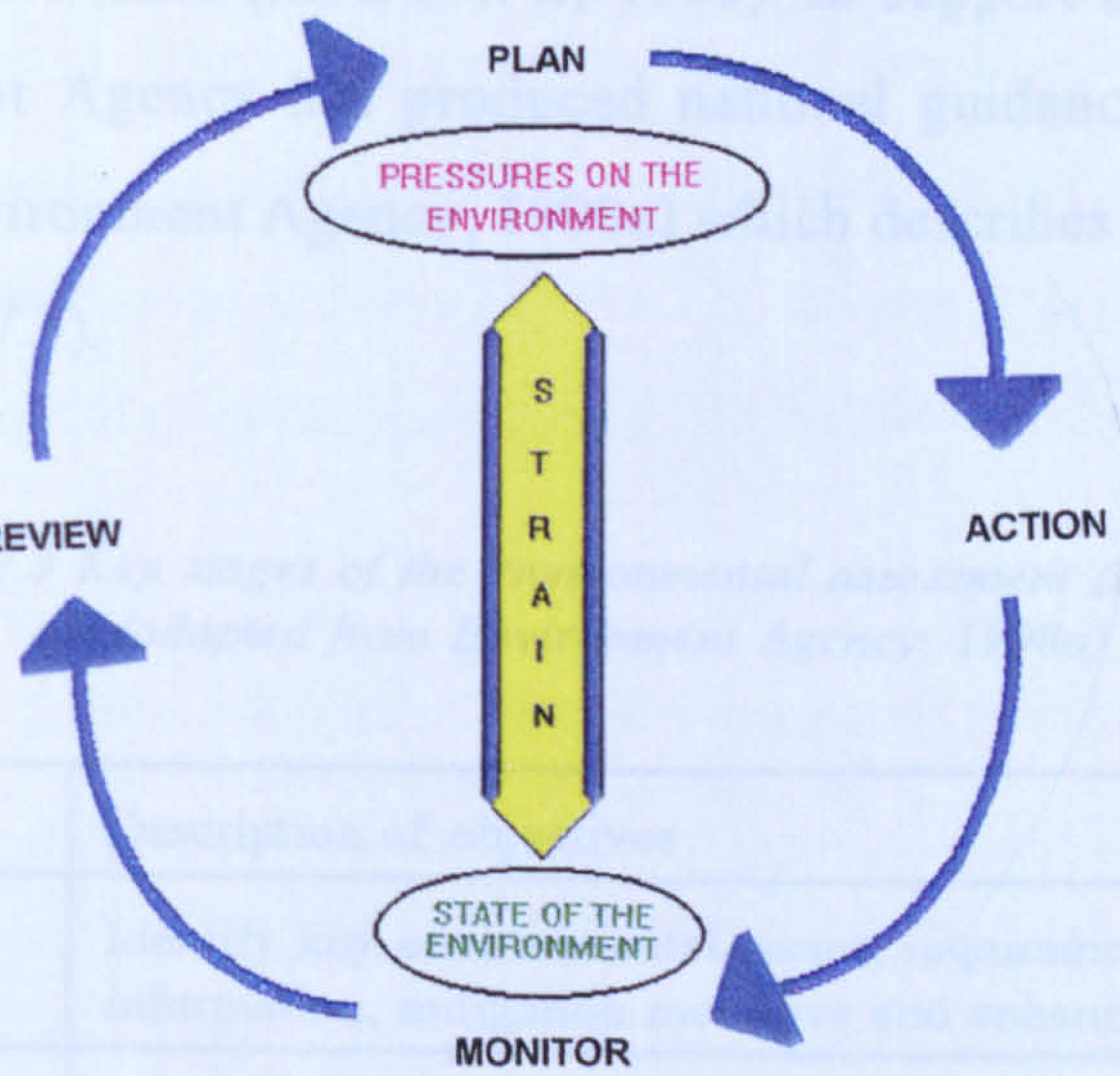


Figure 7.2 The management cycle in relation to environmental performance

A further policy has recently been developed by the Environment Agency in relation to the environmental assessment of its internal works and activities (Environment Agency, 1998e). Although the policy has yet to be implemented nationally, the following Policy Statement has been proposed:

> *The Environment Agency will discharge its environmental assessment (EA) duties under the relevant legislation including SI 88/1199 and SI 88/1217 in a consistent manner and to high standards. EA is seen as integral to the work of the Agency and good practice for EA's for both internal and external projects will be followed. The Agency will expect applicants and developers to adopt equally high standards in the assessment of any environmental impacts of proposed developments."* (Environment Agency, 1998e).

This policy is particularly relevant to river bank erosion because works to the bed or banks of a river fall under The Land Drainage Improvement Works (Assessment of Environmental Effects) Regulations 1988 (Statutory Instrument No. 1217) (HMSO, 1988). This legislation provides a mechanism through which to assess the likely impacts of a proposed project before it is allowed to be implemented. Moreover, it gives the Environment Agency, as the land drainage authority for the navigable River Thames, the responsibility for assessing the potential significance of impacts resulting from bank protection works that it undertakes (MAFF/WO, 1996). In support of this recent policy, the Environment Agency has produced national guidance on environmental assessment (Environment Agency, 1998a) which describes the key stages of the process (Table 7.3).

Table 7.3 Key stages of the environmental assessment (EA) process (adapted from Environment Agency, 1998a)

Stage of EA	Description of objectives
Scoping	Identify key environmental issues, requirements for baseline information, mitigation measures and enhancement opportunities.
Baseline survey & data collection	Collect baseline data as a basis from which to predict impacts and compare with future monitoring.
Impact prediction & assessment	Predict likely impacts on the environment in terms of magnitude and significance.
Evaluation of options	Evaluate and compare impacts of alternative options.
Design of mitigation & enhancements	Identify ways of minimising or eliminating adverse impacts. Assess the magnitude and significance of the residual impacts after mitigation.
Report preparation & decision	Document the results of the environmental assessment, make this information publicly available and decide whether to proceed.
Detailed design & implementation	Design project in detail, including mitigation measures, and implement.
Monitoring & audit	Monitor resulting environment and review against predicted impacts, mitigation expectations and specific success criteria.

Another particularly relevant initiative is the *Tidal Thames Mitigation and Compensation Policy*, recently drafted by the Thames Region of the Environment Agency (1998f). This policy aims to provide a rationale through which to manage the mitigation of, and compensation for, the impacts resulting from the Environment Agency's tidal Thames flood defence capital works programme. The draft policy hinges on a management hierarchy (Table 7.4) so that, whilst a preference is established for the avoidance of impacts, appropriate measures can mitigate or compensate for unavoidable impacts. The aim of the hierarchy is to ensure that there is 'no net loss of habitat' (eg. Hugget, 1998; Smith, 1998). For example, where proposed flood defence works are likely to result in unavoidable encroachment of the foreshore, the environmental assessment process (Table 7.3) allows appropriate mitigation or compensatory measures to be identified from baseline information and impact prediction.

Table 7.4 The tidal Thames management hierarchy (Environment Agency, 1998f)

Foreshore impact management hierarchy	
i)	Avoid adverse impact
ii)	Reduce adverse impact
iii)	Restore environmental assets
iv)	Create replacement environmental assets
v)	Improve remaining environmental assets

Most recently, the Water Management Department of Environment Agency (Thames Region) has initiated the *River Thames Corridor Development Project*. Whilst terms of reference for this project have yet to be established, this clearly shows the considerable momentum behind the development of a framework for managing river bank erosion which embraces the Environment Agency's commitment to sustainable development. Furthermore, if goals for sustainable river management are to be achieved, then the potential contribution from applied geomorphology can not be ignored (Thorne *et al.*, 1997).

7.3 The strategy framework

This section draws on the research findings discussed in the previous chapters, and the relevant sustainability principles and policy guidance discussed above, to develop a framework through which to manage bank erosion on the non-tidal, navigable River Thames.

The framework integrates the principles of environmental management and assessment (Figure 7.2 and Tables 7.3 and 7.4) with the 'pressure-state-response' approach to sustainable development (Table 7.2) adopted by the Environment Agency (1998d) and the risk-based approach to bank erosion management developed by the Environment Agency (1997). Whilst a strategy is presented for the River Thames, the framework has been developed as a transferable tool for river managers and land use planners through which to contribute towards the sustainable development of river corridors.

The framework also integrates the strategic and operational expectations of the river corridor through the environmental management cycle (see Figure 7.2), whereby operational decision-making is underpinned by a rational strategy aimed at delivering continuous environmental improvement. The management strategy for the non-tidal, navigable River Thames is illustrated in Figure 7.3 and described below.

The strategy relies on a number of key elements:

- assessment of the causes and consequences of river bank erosion;
- establishing priorities: high level trade-offs and a plan of how to respond to the causes and consequences of erosion;
- identification of appropriate indicators against which to measure success.

The principle objective of the strategy is to provide direction for operational activities in order that they may collectively contribute to the broader objective of sustainable development.

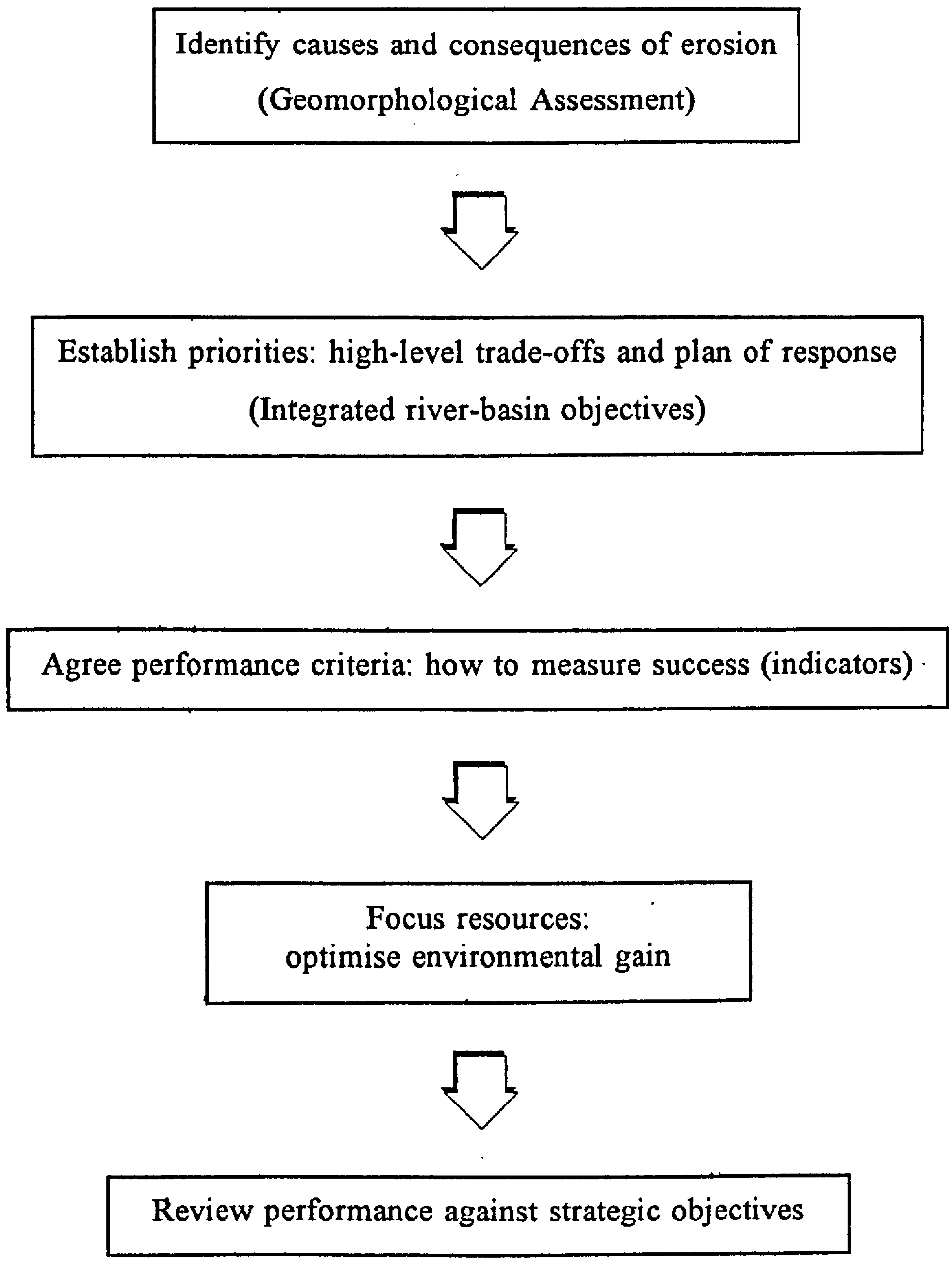


Figure 7.3 Structure of the Thames bank erosion management strategy

i) Causes and consequences of bank erosion on the River Thames

Within any river system numerous 'pressures' operate to produce the resulting 'state' of the environment. Chapter Three reviewed the various factors influencing bank erosion which may be natural or anthropogenic and may act over different spatial and temporal scales. Assessment of the interaction between these pressures and the physical environment is a prerequisite to understanding the behaviour of a river system and establishing a rational bank erosion management strategy (Figure 7.4). For example, if bank failure is a result of regrading of the channel bed downstream and nick-point recession of the bed towards the headwaters, then the problem is one of reach-scale channel instability as opposed to localised bank instability. Consequently, measures designed to address the problem must consider reach or catchment-scale channel adjustment in response to change (eg. Downs and Brookes, 1994). In addition, whilst it may remain a difficult task to judge whether channel characteristics are indicative of current and future adjustment or are relics left by past processes, consideration of upstream and downstream conditions and historical evidence (Figure 7.4) can improve the reliability of such judgements (Downs and Thorne, 1996).

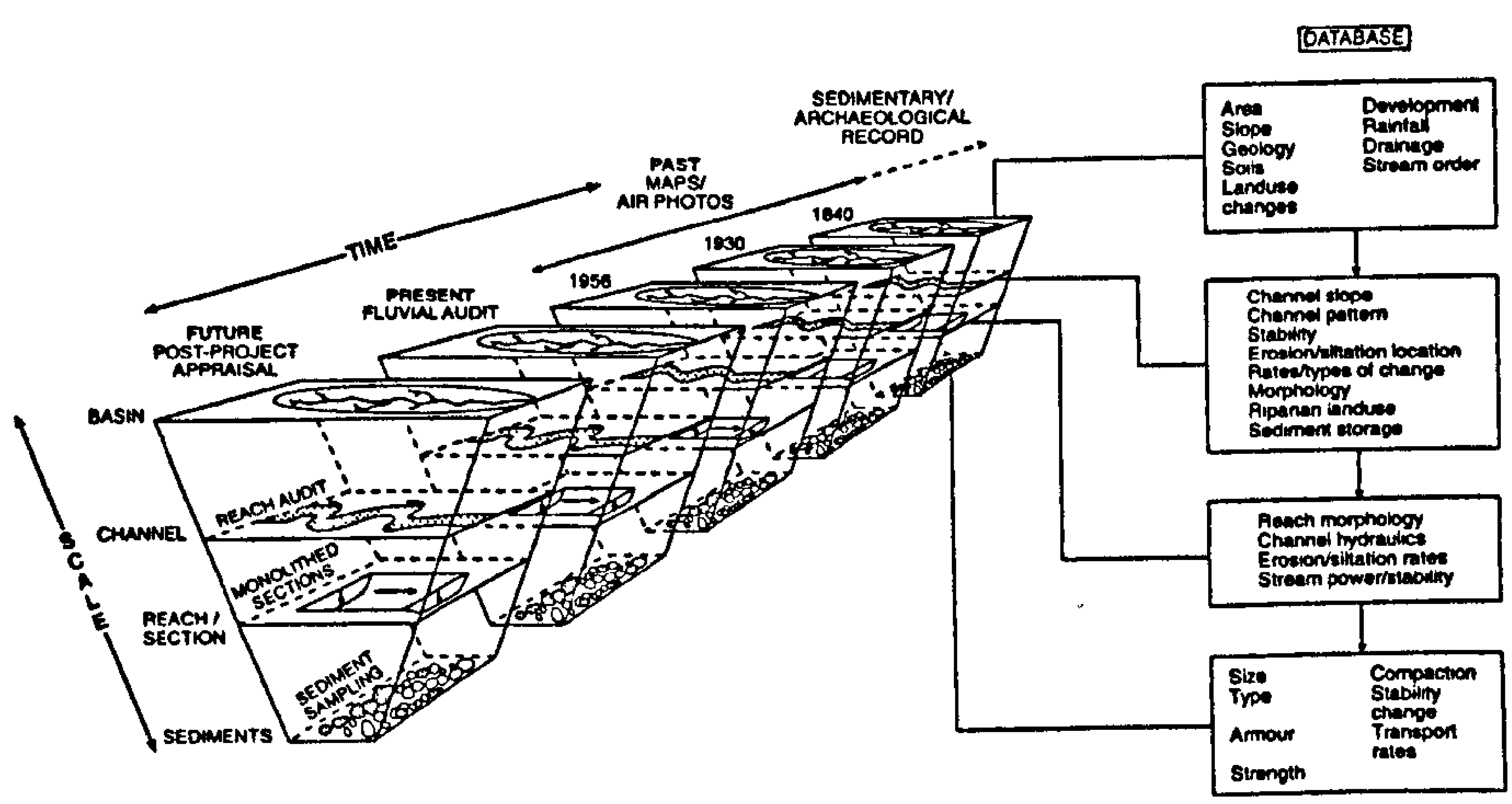


Figure 7.4 The geomorphological framework for rational river management (Sear, 1996)

Various geomorphological assessment techniques can be used to evaluate the geomorphological sensitivity of river systems and develop sustainable management recommendations (eg. Downs, 1995b; Newson, 1998). These techniques include catchment baseline surveys, fluvial audits (eg. Sear, 1992; Downs and Brookes, 1994; NRA, 1995) and more detailed assessments of hydraulic geometry and channel dynamics (Brookes and Long 1990; Downward, 1993).

Figure 7.5 illustrates the suite of techniques available and their contribution to river restoration planning. The 'catchment approach' provides a basis on which to investigate channel conditions in the light of spatial and temporal change, and allow classification and prioritisation according to the original performance criteria.

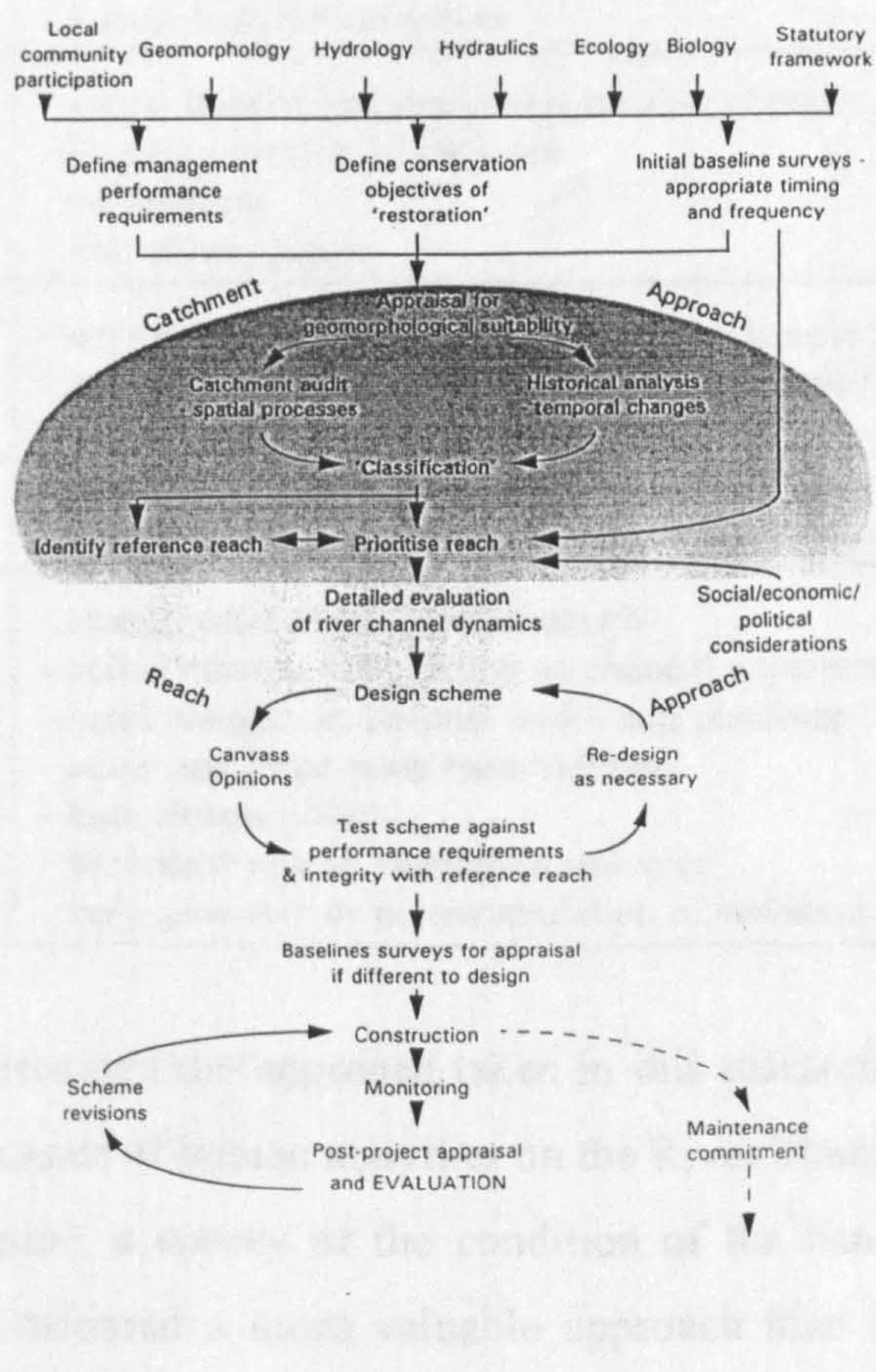


Figure 7.5 Geomorphological assessment as a tool to problem solving: the graded oval shows the transition from a catchment approach to a reach-centred approach (Kondolf and Downs, 1996)

The issue of catchment or reach-scale channel stability was recognised in the framework developed by the Environment Agency (1997) which requires an assessment of the channel status. The framework identified five categories of channel status and the various diagnostic features of each (Table 7.5), although the various decision trees discussed in Chapter Six (Appendices 6.1 and 6.2) make no specific use of this information.

Table 7.5 Channel status and diagnostic features (Environment Agency, 1997)

Channel status	Diagnostic features
Stable (natural and engineered)	- no or localised evidence of channel or bank erosion - straight or meandering - dense vegetation cover on banks and on channel bars - low stream power
Recovering (natural and engineered)	- evidence of previous bank failures - straight or meandering - vegetation establishing on banks and on channel bars - deposition at basal end-point - low or high stream power
Natural and vulnerable	- active erosion and deposition causing changes in width/planform - localised erosion of bank toe - meandering - low stream power
Natural and unstable	- active erosion and deposition causing changes in width/planform - several small-scale bank failures or few large failures - meandering - high stream power - very low rate or no accumulation of sediment at basal end-point
Engineered and unstable	- straightened or modified channels - active erosion / deposition as channel adjusts to increase sinuosity - rapid changes in channel width and planform - many and large scale bank failures - high stream power - very slow rate of vegetation recovery - very slow rate or no accumulation of sediment at basal end-point

Chapter Two discussed the approach taken in this research where, because of the historic influence of human activities on the River Thames, and particularly on its flow regime, a survey of the condition of the banks along the River Thames was considered a more valuable approach than the fluvial audit to gaining an understanding of the influences on bank erosion. The regulated flow regime and resulting low stream power (Figure 5.1) suggests that reach-scale morphological adjustment through processes of erosion is unlikely along the non-tidal, navigable River Thames. However, Chapter Four presented some evidence to suggest that past channel dredging, and the resulting lowering of the water level, may have contributed to local changes in bank morphology, including reduced marginal vegetation and bank erosion.

Monitoring of erosion at several sites along the river over 0.8 to 1.4 years suggested that rates of erosion are generally less than 0.2m/yr (see Figure 4.10). Rates of erosion up to approximately 0.5m/yr were estimated at some sites, although these are probably the most extreme experienced along the non-tidal, navigable River Thames and historical evidence of the channel planform suggests that they could not be representative of rates of bank retreat in the past. The pattern and distribution of bank erosion at the sites suggests no simple cause and effect mechanisms in terms of the influence of weakening and weathering processes, fluid entrainment and mass failure. However, observations indicated that high flow discharges were not necessarily the most dominant causes of erosion. For example, weakening and weathering processes were a particularly important contributory factor in the toe erosion and subsequent mass failure observed under medium flows at the Lower Wallingford monitoring site. It may be that the accelerated rates of erosion measured here and at the Laleham monitoring site are associated with the adjustment of the bank morphology following a decline in marginal vegetation as a result of dredging activities.

Monitoring also demonstrated the influence of bank material, geometry and vegetation on erosion processes. For example, at the Laleham monitoring site, which has low, sloping banks, the erosion of the sandy toe material resulted in retreat of the thin, cohesive, root zone. Alternatively, the clay material at the toe of the high, steep, unvegetated banks at the Lower Wallingford site suffered from tension cracks due to desiccation. Such weathering processes had relatively little effect on the well drained banks at Chertsey which, although also largely unvegetated, were less cohesive. Whilst the influence of vegetation was not investigated in any great detail and at the majority of sites the face of the bank was unvegetated, erosion rates were significantly reduced where the bank face was vegetated.

Whereas the site-specific monitoring of erosion processes recognised the role of bank material type and the contribution to erosion from weathering processes, the survey of the Thames' banks (Volume II) did not specifically catalogue these aspects. However, the extent of bank vegetation does give some indication of the potential susceptibility of the banks to weathering processes. The survey identified erosion along approximately 10% of the total length of bank from St. John's to Teddington Lock. Nearly 40% of this length is associated with unprotected, unvegetated banks, and the length of bank erosion decreases progressively as the complexity of the bank vegetation increases, i.e. from grass to shrubs, to sparse trees, then to wooded banks (Figure 5.16).

Whilst characterisation of the causes of bank erosion on the River Thames remains a difficult task, this research has suggested that the susceptibility of the banks to erosion depends on the bank geometry and the nature of the bank material and vegetation. The bank survey allowed factors contributing to erosion to be classified according to three categories: (1) channel planform and geometry, (2) land and bank use and (3) navigation activities. The majority of bank erosion recorded (~82%) was attributed to a combination of factors from at least two of these categories, with ~28% of the length attributed to a combination of factors from all three, which demonstrates the complex nature of bank erosion along the Thames. The location of the erosion suggests no obvious spatial trend, although whereas cattle grazing tends to dominate the land and bank use activities along the upper reaches of the Thames, angling and amenity access tends to dominate land and bank use activities along the lower reaches. Furthermore, the proportion of eroding bank along the lower reaches tends to be slightly lower than along the upper reaches (Figure 5.14). The likely reason for this is that the significantly higher proportion of bank protection along the lower reaches offers less opportunity for bank erosion than along the largely unprotected upper reaches. Figure 5.15 also suggests that, in general, the causes of erosion become more complex towards the lower reaches of the Thames.

Whilst bank erosion at any one site on the River Thames may be the result of the complex interaction of processes, this research allows some generalisations to be made about the key factors identified from the survey as contributing to bank erosion. Chapter Five compared the near-bank shear stresses generated by parallel flows with those generated by boat wash along the Thames. Near-bank flow velocities measured downstream of Wallingford Bridge at ~60% bankfull discharge generated an average near-bank shear stress of 0.66N/m^2 and a peak of 1.66N/m^2 (Table 5.6). Comparing these shear stresses with the critical shear stresses of soils investigated by Arulanandan *et al.* (1980) suggested that this parallel flow was probably not capable of removing intact material from the surface of the bank, but may be capable of removing loosened particles (Figure 5.10). Higher near-bank shear stresses would be expected as a result of higher flow discharges (up to bankfull) and impinging flows due to the channel planform and geometry. In these circumstances, near-bank shear stresses would be more likely to reach or surpass the critical shear stress of Arulanandan's soils (~2N/m^2). Near-bank shear stresses generated by boat wash along the River Thames were generally lower than those generated by the parallel flows measured at Wallingford (Table 5.6). 'Characteristic' boat wash generated near-bank shear stresses of up to ~0.6N/m^2, and well below the critical shear stress of Arulanandan's soils. In a very small number of incidents, traffic produced wash that was considered 'uncharacteristic' boat wash for the Thames, generating peak near-bank shear stresses of 2-5N/m^2. Arulanandan's investigations suggest that shear stresses generated from this 'uncharacteristic' boat wash would be likely to result in erosion of intact particles from the surface of the bank material.

Generally, therefore, and not withstanding the influence of bank material, geometry and vegetation, the potential severity of erosion can be considered greatest where flow impinges on the bank, or where there is a high degree of turbulence for example, downstream of a weir. The potential severity of erosion due to 'characteristic' boat wash is considerably lower. High intensity 'uncharacteristic' wash could generate similar near-bank shear stresses to those generated by impinging flows, but the low frequency of such events means that the overall potential severity of erosion due to navigation activities is relatively low.

The potential for erosion to result from the land and bank use is more difficult to determine from this research. Nonetheless, Table 7.6 (see below) ranks the severity of such erosion as medium: between that associated with the channel planform and geometry (high severity) and navigation activities (low severity). The rationale for this is that whilst this research did not specifically quantify the shear stresses applied during mechanical damage of the banks, observations of cattle trampling at St. Johns and amenity access at Wallingford suggested that mechanical damage was an important preparatory factor in erosion of the bank material under medium and high discharges. The bank survey did identify some shearing of the surface of the bank material as a result of boats mooring, but evidence of the mechanical damage associated with non-navigation related activities, eg. cattle trampling and angling suggested that, on the whole, the potential severity of erosion resulting from non-navigation related activities was greater than that associated with navigation activities.

This research, therefore, allows the development of a severity ranking for the causes of erosion along the Thames (see Table 7.6), which is based on the potential for erosion discussed above. In summary, the severity of the causes of erosion tends to decrease from that associated with (1) channel planform and geometry, to (2) land and bank use, to (3) navigation activities. Alternatively, the length of bank erosion influenced by these factors increases: Navigation-related activities influence ~90% of the total length of erosion, with land and bank uses being associated with ~65% of the length of bank erosion and channel planform and geometry ~50%.

Table 7.6 Risk matrix describing the causes and consequences of bank erosion on the River Thames

Severity of threat posed by continued erosion		Probability of erosion occurring according to cause of erosion		
		HIGH Channel planform & geometry	MEDIUM Land & bank use	LOW Navigation related
- Integral flood defence bank - Buildings/properties: residential/commercial - Structures: weirs, bridges etc - Infrastructure: metalled roads, railways etc. - Water quality: pollution to surface waters	**HIGH**	HIGH RISK	MEDIUM RISK	LOW RISK
- Non-metalled public rights of way/bridleways - Designated heritage/ conservation sites - Navigation activities	**MEDIUM**	MEDIUM RISK	MEDIUM RISK	NO RISK
- Recreation: formal/informal - Agricultural land: arable/pasture - Gardens and allotments	**LOW**	LOW RISK	NO RISK	NO RISK

The review of the performance of a selection of erosion control techniques adopted along the banks of the River Thames also provides valuable information in relation to the management 'response' to bank erosion, or the consequences of erosion management. Chapter Six suggested that whilst the design of specific erosion control techniques was relatively successful in terms of erosion prevention, inappropriate strategies tended to be adopted with excessively high factors of safety and environmental impact (see Figure 6.1).

New guidance on the assessment and management of bank erosion (Environment Agency, 1997) was used to investigate the problem solving process, and suggested that the severity and consequences of erosion along the River Thames tended to be over-estimated. For example, only 6 of the 26 erosion management strategies investigated in this research were considered to be the optimum strategies available (see Figure 6.1). The other 20 strategies adopted heavier engineering techniques than were considered necessary for the circumstances, thus, also resulting greater environmental impacts than necessary. Likewise, at 14 of the 21 bank erosion monitoring sites investigated in this research, erosion of footpaths was the only threat posed by continued erosion (see Appendix 6.4). Furthermore, whilst measures to mitigate impacts on the river corridor tended to be incorporated into the over-engineered solutions, additional environmental enhancements were seldom included (see Figure 6.2).

The consequences of management intervention investigated in Chapter Six suggests that the morphological, environmental and conservation value of the river corridor will continue to deteriorate if existing practices continue.

Whilst the Environment Agency's (1997) bank erosion management framework facilitates a somewhat subjective determination of the consequences of erosion, this research has developed a more prescriptive determination of the consequences, which is included in Table 7.6. The rates of bank erosion reported in Chapter Four and the investigations discussed in Chapters Five and Six provide the rational behind this prescriptive determination, so that only in the most extreme cases would the consequences of erosion be considered 'severe' in the Environment Agency's (1997) framework (see Appendix 6.1). Such cases would include where human life would be threatened if the rate of bank erosion continued, for example if the bank was integral to the flood defence so that its continued erosion would place life and property at immediate risk of flooding.

For example, Chapter Six included a review of erosion control Case study no. 17 where a narrow peninsular of land separated flow upstream of Cookham weir from flow downstream. In this case, whilst a single event would have been very unlikely to cause sufficient erosion to result in a breach of the peninsula, the long term risk associated with continued erosion were not considered acceptable. The risk posed by continued erosion can be considered the product of the severity of the erosion and the consequences of erosion. Consequently, realistic timescales are extremely important in determining risk, since no matter how significant the implications of erosion, if the erosion is not likely to occur, then the risk is eliminated.

ii) Establishing priorities and high-level trade-offs

The fluvial-sediment system creates the morphology on which other systems depend. Consequently, effective river management relies on the integration of the principles of geomorphology with other disciplines so that management objectives complement the wide-ranging functions of the river, including flood defence, navigation, fisheries and conservation (Newson, 1994; Newson *et al.*, 1997). Geomorphological assessment techniques can be used to complement information from fisheries, biological and river corridor surveys by integrating physical process (Haltner *et al.*, 1996). In terms of bank erosion, the contribution from geomorphology allows an assessment to be made of the causes and consequences of the erosion. This, in turn, provides the relevant information to identify alternative management strategies and evaluate their merits in the light of broader sustainability objectives.

A strategic approach to river management facilitates multi-functional planning of broad environmental objectives so that priorities are identified and trade-offs between competing long-term aspirations are rationalised at a higher level. In this way, repetitive and costly negotiations are avoided at the operational level. Such an approach was recently adopted for the Galaure River, a tributary of the Middle Rhône (Piégay *et al.*, 1997), where geomorphological zoning of river dynamics allowed community aspirations and conservation interests to be integrated into a cost-effective management plan.

In the case of the River Thames, management aspirations need to be established within the context of these broader sustainability objectives. Due to the self-adjusting nature of fluvial systems it could be argued that, for a river to be truly sustainable, natural fluvial process should be allowed to proceed without intervention. However, the River Thames is a relatively stable channel, impounded for navigation and largely constrained, thus exhibiting limited reach-scale dynamics. Bank erosion tends to be localised and, whilst some erosion can be attributed solely to adjustment of the channel planform and geometry (eg. erosion along the outside of a bend), the majority of erosion can be attributed to land and bank use and navigation activities. Indeed, this research has suggested that, whilst over short to medium time scales (up to 50 years) there may be localised adjustment of the bank through processes of erosion, in general, and certainly over longer time scales (say 50 to 100 years), bank erosion does not contribute significantly to catchment-scale processes that sculpture the morphology of the channel. Consequently, in recognition of the constraints on the River Thames a more simplistic interpretation of sustainability is adopted here, whereby sustainability is considered synonymous with the protection and improvement of the environment. In practice, this approach translates into a presumption for allowing bank erosion to continue without intervention unless the risk of continued erosion is unacceptable.

The availability of appropriate information relating to the 'state' of the environment of the River Thames means this multi-functional planning is not necessarily straight forward (Environment Agency, 1998b). Nonetheless, various data sets are available of specific relevance to the quality of the River Thames corridor. These include data relating to habitats, biological and chemical river quality and fisheries. Comparison between various 'state' of the environment indicators and the data generated in this research to characterise the river banks allows actions to be prioritised more effectively, in terms of achieving environmental improvement. For example, enhancements could be targeted at locations where the morphology of the river bank was degraded and where the quality of the fishery was poor. Whilst regulation of the flow means that there is little potential for significant change along the Thames in terms of reach-scale geomorphological sensitivity, this research suggests that strategic management objectives for the banks of the river Thames could realistically focus on a number of key aspects:

a) Flood plain restoration

Evidence, primarily in the form of dated photographs, paintings and sketches suggests that dredging the channel over the last century and the resulting lowering of the level of the water surface may have resulted in a reduction in marginal vegetation. Land use within the Thames catchment is largely urban and agricultural and, hence, predominantly fine sediments are supplied to the river system. The low channel gradient, increased channel capacity through dredging, and impounding structures along the course of the river means that fine sediments tend to be deposited along the river bed, requiring removal for navigation purposes. Restoration of flood plain would encourage accretion of suspended sediments during over-bank flows and, thus, reduce the requirement for de-silting. Whilst small-scale flood plain restoration schemes may not offer significant financial return in terms of reduced expenditure on de-silting, reach-scale restoration plans could offer a return on investment if targeted effectively.

For example, the assessment of factors contributing to erosion at various sites along the Thames (Chapter Five) identified significant lengths where the river bank was grazed by cattle and, therefore, offers little or no habitat diversity. For example, at Bank erosion site nos. 34 and 35 along Eynsham Reach (Map 8, Volume III) and nos, 42 and 43 along Osney Reach (Map 11, Volume III), over-widening of the channel has been facilitated by boat wash which acts at the level of the water surface, typically creating a spending beach at the toe of the bank. At these locations, reducing the channel width by creating marginal shelves to function in a similar manner to a flood plain would encourage deposition of fine sediments on top of the marginal shelves and increase flow velocities at the centre of the channel, encouraging sediment transport along the line of navigation.

Where the ecological benefits associated with erosion are not particularly high, for example, in the case of cattle trampling which does not permit natural recovery of the river margins, consideration should be given to preventing erosion and reinstating the flood plain. Targeting of enhancements would require information relating to navigation depths and sediment sizes along the length of the channel. Whilst such information is not yet widely available, the author is contributing to a recent Environment Agency (Thames Region) initiative to refine survey information for the River Thames. At present, only one reach of the River Thames has been mapped to show channel depth contours and bed substrate, but the quality of this preliminary output suggests that the data will provide useful management information for targeting flood plain restoration. Calculating the volume of fine sediment that compromises the navigation depth will allow problem reaches to be targeted for restoration. Development has seen much of the river's natural flood plain function replaced with drainage infrastructure and sewage treatment works. Hence, a further study should be undertaken to investigate the impact of sediment loads from urban drainage systems and sewage treatment works along the River Thames.

b) Riparian buffer strips

The value of buffer strips for habitat purposes and pollution abatement is well recognised (Environment Agency, undated a). Whilst water quality along the River Thames is relatively good, filtering of contaminants from diffuse pollution sources such as agricultural runoff should be a strategic management objective. Creation of buffer strips should be targeted along nitrate sensitive areas and those experiencing pollution from diffuse sources such as the use of agrichemicals. Whilst locations of nitrate sensitive areas are readily available in a GIS format, diffuse pollution sources have not been mapped. As an alternative, surrogates could be used describing the vulnerability of the environment to contamination. For example, Groundwater Protection Zones, based on the vulnerability of the groundwater aquifer to contamination, or the presence of a particularly pollution-sensitive species.

c) Reduce high-wave boat wash

The boat wash monitoring exercise (Chapter Five) suggests that 'uncharacteristic' wash generated by speeding boats was probably capable of driving bank erosion (Figure 5.10). Furthermore, navigation-related bank erosion was particularly prevalent along reaches with intense recreational and competitive boating (eg. near Henley). Whilst bank erosion may have benefits in terms of conservation, boat wash tends to lead to channel widening by erosion of the bank at the level of the water surface and, therefore, contributes to the sediment related navigation problems discussed in (a), above. Consequently, strategic management objectives should target banks most vulnerable to intense boat wash.

d) Experimental use of in-channel structures

No in-channel bank erosion control structures have been used on the River Thames. Whilst groynes and bend-way weirs have been installed along other rivers, including the Rivers Roding, Wraysbury and Colne in the Thames basin, further experience is required in the application of these techniques. Consequently, management objectives should include the experimental use of such structures. To this end, the author proposed the use of groynes along the outside of a bend immediately downstream of Pinkhill Weir. The groynes were proposed to dissipate flow energy downstream of the weir and draw the thalweg away from the outer bank and closer to the centre of the channel. However, subsequent site investigations revealed a substantial volume of concrete blocks protecting the toe of the bank, thus, negating the need for additional engineering measures. The potential to use similar in-channel devices remains to be established and this will be investigated as part of the feasibility study for the refurbishment of King's Weir.

iii) A plan of response

Consideration of the causes and consequences of bank erosion along the River Thames facilitates the selection of an appropriate plan of how to deal with an erosion situation. Chapter Six highlighted the use of over-engineered solutions to erosion problems which result in unnecessary adverse environmental impacts. This research has allowed a risk-based erosion management hierarchy to be developed for the Thames which considers the severity of the causes and consequences of erosion to identify the most appropriate management strategy (see Table 7.7). The hierarchy incorporates the presumption against intervention with the concept of medium to long-term 'recovery' of environmental systems. In this way, a preference is established for erosion control that retains a natural river bank but may also result in short to medium-term damage to the river corridor (eg. bank regrading and tree loss), as opposed to erosion control that compromises the long-term naturalness of the river bank for short or medium-term gain. The underlying principles behind the preference hierarchy are no different to those behind the approach taken by the Environment Agency (1997), but the results of the research presented in previous chapters allows management strategies to be tailored more specifically to the severity of the causes and consequences of erosion.

Such a hierarchy is needed at the catchment-scale in order to identify the implications of such an approach to river users and the environment. For example, whilst navigation-related activities are relatively important contributors to bank erosion along the River Thames (contributing to ~90% of the length of bank erosion), the issue of navigation is irrelevant in the management strategy for a river that is not navigable. Alternatively, a management strategy for a stable river with a highly developed floodplain could legitimately advocate the prevention of meander migration, whereas such a strategy might be entirely inappropriate and prohibitively expensive to implement along a dynamic, meandering channel. In such cases, it may be more appropriate to designate management zones, whereby different strategies are prescribed for different reaches (eg. Piégay *et al.* 1997).

The aim of the plan is to ensure that mitigation and enhancement measures are considered as a consequence of the overall 'response' to the 'pressure' of bank erosion, rather than as an 'add-on' at the end of the design of the solution. In this way, the environmental assessment process can begin to evaluate the costs and benefits of alternative erosion control strategies in the light of broader management objectives. For example, in some circumstances it may be appropriate to trade the detrimental impacts associated with erosion control at one particular site with the improvements offered by mitigation and enhancement at another site.

The multi-functional catchment planning process discussed above, which identifies strategic priorities and objectives, is essential in order that mitigation and enhancement measures achieve optimum results in terms of environmental improvement.

The Environment Agency (1997) provided guidance on the selection of a specific erosion control technique according to the bank characteristics (loading, height and slope) and river environment (average bankfull velocity) (see Appendix 6.2). Table 7.7 has been developed from this research specifically for the non-tidal River Thames and provides a framework through which to select the most appropriate erosion control technique for a particular river and bank environment based on the risks associated with the continued erosion.

In a manner similar to the way that Table 7.7 identifies several types of river environment along the Thames (including, for example, lock-cuts and weir streams), various 'functions' can be attributed to reaches of any river. Whilst this classification is particularly clear for the River Thames and has been demonstrated by the research, the use of appropriate geomorphological assessment tools facilitates this process for any river system (see Figure 7.5).

Table 7.7 Bank erosion management hierarchy for the River Thames (see Appendix 7)

River / bank environment	**Hierarchy of erosion management strategies according to the risk associated with erosion (see Table 7.6)**			
	HIGH RISK	**MEDIUM RISK**	**LOW RISK**	**NO RISK**
High probability of erosion occurring: - weir stream - impinging flow - adjacent to scour pool - turbulence at structures - outside bank of bend	- Regrade bank slope - In-channel structures - Bioengineering - Biotechnical engineering - Structural engineering	- Allowed natural adjustment - Regrade bank slope - Relocation - Bioengineering	- Allowed natural adjustment - Relocation	N/A
Medium probability of erosion occurring: - livestock access - general public amenity - angling	N/A	- Allowed natural adjustment - Management - Relocation - Bioengineering (or biotechnical engineering against cattle)	N/A	- Allowed natural adjustment - Management
Low probability of erosion occurring: - boat wash - mooring - lock cut	N/A	N/A	- Allowed natural adjustment - Management - Bioengineering	- Allowed natural adjustment - Management

Whilst Chapter Six reported relatively favourably on the inclusion of mitigation measures into erosion control techniques, the environment was rarely enhanced as a result of the solution. A mitigation and enhancement plan has, therefore, been developed as part of the erosion management strategy (Table 7.8). The performance criteria listed in Table 7.8 are the same as those used to assess the performance of the case studies reviewed in Chapter Six.

Table 7.8 Mitigation and enhancement criteria for alternative erosion control techniques

<table>
<tr><th colspan="2" rowspan="3">Erosion control strategy/technique & severity of impact</th><th colspan="4">Additional mitigation & enhancements required for performance ranking</th></tr>
<tr><th colspan="3">Mitigation ranking</th><th>Enhancement ranking</th></tr>
<tr><th>LOW</th><th>MEDIUM</th><th>HIGH</th><th>LOW-MEDIUM-HIGH</th></tr>
<tr><td>Natural adjustment
Management
Relocation</td><td>No impact</td><td>N/A</td><td>N/A</td><td>N/A</td><td rowspan="7">Low performance = inclusion of no additional measures.

Medium performance = inclusion of minor improvements (eg. MP), but no contribution to strategic management objectives.

High performance = inclusion of improvements (additional to mitigation) that contribute to the strategic (multi-functional) management objectives: flood plain restoration; buffer strips; etc.</td></tr>
<tr><td>Channel realignment/ obstruction removal
Bank regrading</td><td>No impact</td><td>N/A</td><td>N/A</td><td>N/A</td></tr>
<tr><td>Bioengineering techniques, eg. willows and faggots</td><td>Low</td><td>None</td><td>None</td><td>None</td></tr>
<tr><td>Planted rock/coir rolls</td><td>Low</td><td>None</td><td>None</td><td>None</td></tr>
<tr><td>Geotextiles</td><td>Medium</td><td>None</td><td>None</td><td>MP</td></tr>
<tr><td>Riprap, gabions, cellular concrete</td><td>Medium</td><td>None</td><td>None</td><td>MP</td></tr>
<tr><td>Hard (structural) engineering: sheet piling, concrete etc.</td><td>High</td><td>None</td><td>MP</td><td>RN</td></tr>
</table>

Note: MP = marginal planting, or other minor mitigation measures, but not re-naturalisation (RN) of the bank.

iv) Performance criteria

Guidance on measuring environmental performance through the 'pressure-state-response' framework was formulated in the *Thames Environment 21* strategy (see Table 7.2) and is therefore generally applicable to the River Thames environment. The *Thames Environment 21* strategy identified three indicators which have been applied in this study: (1) the 'pressure' of recreational use on the river corridor, (2) the length of natural river bank (as an indicator of the 'state' of the environment) and (3) enhancement of the river corridor (as an indicator of the 'response' to environmental deterioration).

Clearly, the application of different indicators may be more appropriate in different river environments and a strategic geomorphological assessment (see Figure 7.5) provides the basis on which to classify the river and establish appropriate environmental indicators.

The significant proportion of structurally-protected banks along the River Thames (see Figure 5.3) means that the use of an indicator such as the length of natural bank is entirely appropriate. Furthermore, whilst alternative indicators of environmental quality are available, consideration should be given to ensuring that the indicators are: (1) realistic relative to the expectations of the river environment, and; (2) meaningful to stakeholders and those involved in decision-making (Clark, 1995). For example, whilst a dynamic gravel-bed river may be most desirable in terms of habitat value, a technique such as the River Habitat Survey, which scores the quality of the river habitat according to morphological diversity (amongst other things such as vegetation structure), is inappropriate as a tool for environmental performance monitoring along the River Thames corridor. The Thames is an impounded, lowland river and, without compromising its navigation function, it would be unrealistic to expect the channel to ever exhibit a great deal of morphological diversity.

A standard Geomorphological Sensitivity Assessment methodology has been applied to a number of catchments in the Thames basin (Brookes and Long, 1990; Downward, 1993) and has now been adopted nationally by the Environment Agency (Brookes, 1996). However, the homogenous nature of the non-tidal, navigable Thames means that the geomorphological sensitivity ranking would be similar along the entire length of the channel and would be unlikely to improve in the future without significant changes to the river regime. The use of such a ranking to measure environmental improvement would, therefore, be inappropriate.

Furthermore, using the length of natural bank as an indicator of quality is more easily understood by other disciplines and local communities than the ranking described by the geomorphological sensitivity assessment. The management strategy for bank erosion on the River Thames, therefore, uses the indicators listed in Table 7.9 within the 'pressure-state-response' framework.

Table 7.9 Pressure-state-response indicators for bank erosion management along the non-tidal River Thames

Pressure: factors influencing bank erosion - channel planform and geometry - land and bank use - navigation
State (strain): consequences of pressure and response - character of river bank (natural/protected) - risk to flood defence, navigation, recreation, wildlife etc. (see Appendix 6.2)
Response: performance of erosion control solutions - compliance with strategy recommended by national guidance (Environment Agency, 1997) - compliance with design criteria and expectations - appropriate mitigation of impacts - environmental enhancement

7.4 Strategy implementation

The Environment Agency's LEAP process (Figure 7.1) is a key mechanism through which to implement the bank erosion management strategy for the River Thames. However, issues relating to the River Thames are addressed through five separate LEAPs which form part of the collection of LEAPs covering the whole Thames basin. Consequently, whilst actions are delivered locally through the LEAP process, the multi-functional planning aspects described in Section 7.3, above, would be best achieved through the *River Thames Corridor Development Project* (Section 7.2) recently initiated by the

Environment Agency (Thames Region). Whilst the terms of reference for this project have yet to be developed, the project will take a catchment-scale approach and it is likely that it will aim to deliver environmental improvement at the local level through the well - established LEAP process.

The Environment Agency presently operates through a series of *Functional Action Plans* developed by each of its core functions (eg. Flood Defence, Fisheries, Conservation and Environmental Protection). These *Functional Action Plans* assist in the prioritisation of actions in the LEAP process and drive the Environment Agency's business planning process. The *Environmental Strategy for the Millennium and Beyond* (Environment Agency, undated b) describes a 'thematic' approach to environmental management, whereby functions are replaced by environmental 'themes' which are based on the Environment Agency's key duties and responsibilities (Table 7.10). This 'thematic' approach superseded the sustainability principles developed in the *Thames Environment 21* strategy, although the approach is very similar. Consequently, an "Integrated River-Basin Management" theme has replaced many of the sustainability principles relating to water management, including flood defence, navigation, and recreation.

Table 7.10 The Environment Agency's nine 'themes' for environmental management (from Environment Agency, undated b)

Addressing climate change
Improving air quality
Managing our water resources
Enhancing biodiversity
Managing our freshwater fisheries
Delivering integrated river-basin management
Conserving the land
Managing waste
Regulating major industry

Figure 7.6 illustrates the role of the River Thames bank erosion management strategy in delivering integrated river-basin management within the hierarchy of strategy initiatives described in Section 7.2.

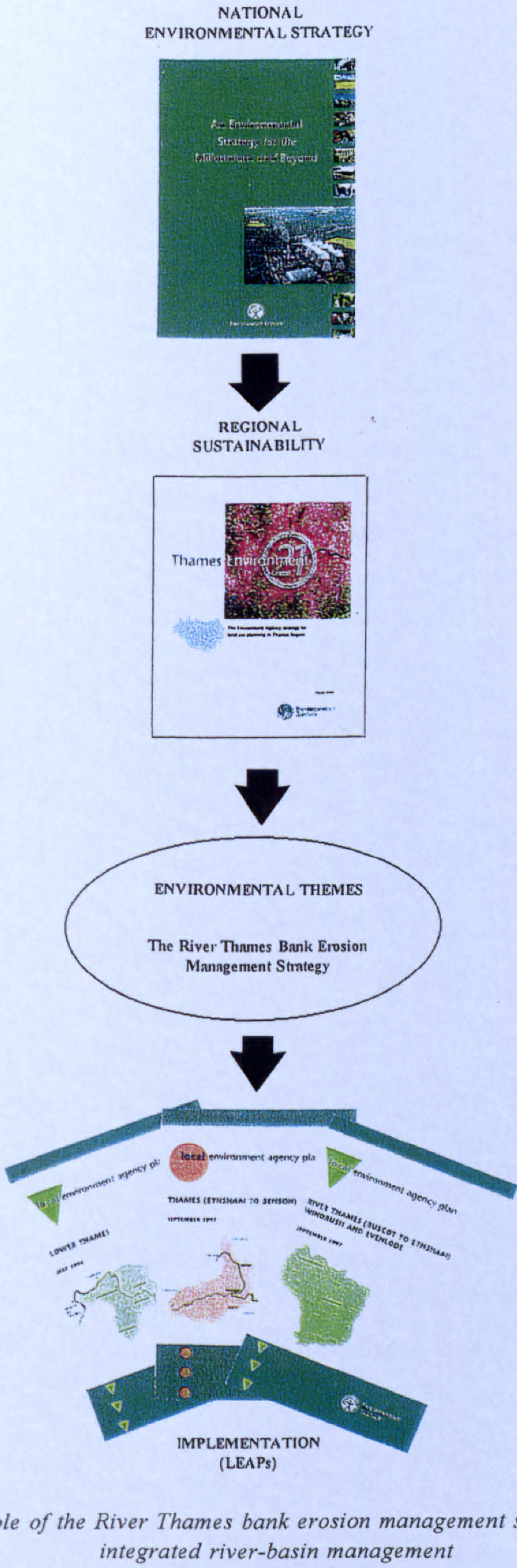


Figure 7.6 The role of the River Thames bank erosion management strategy in delivering integrated river-basin management

The erosion management strategy can be implemented at the operational level through the Environment Agency's internal environmental assessment process and the land drainage consenting processes. The River Thames Reach Assessment has been prepared in support of the erosion management strategy and is presented as Volume III of this thesis. This volume includes information presented in previous chapters (i.e. Figures 5.1 to 5.5 and Figures 5.13, 5.14, 5.15 and 5.17) and the key elements of the management strategy described in this chapter (Tables 7.6 to 7.8). Additional information is also included relating to the 'pressures' on, and 'state' of, the environment for each reach of the River Thames.

The River Thames Reach Assessment (Volume III) follows the convention adopted by LEAPs and 'State of the Environment' reporting, whereby the 'state' of the environment is considered before the 'pressures' on the environment, with the 'response' considered last. This is a logical approach because information at the catchment-scale is a pre-requisite for establishing appropriate environmental indicators and developing a realistic vision for the future. It is only then that effective responses can be planned to realise that vision.

7.5 Research conclusions

This research has used a selection of techniques to investigate bank erosion along the non-tidal, navigable River Thames from St. John's to Teddington Lock. Detailed site-specific monitoring provided insight into river bank processes and the causes of bank erosion over short time scales. Alternatively, extensive survey facilitated spatial analysis of the effects of erosion, from which to infer causal mechanisms. Average rates of bank erosion up to 0.5m per year were measured at some sites which, historical evidence suggests, could not be representative of erosion rates in the past. Accelerated rates of erosion could, therefore, indicate that adjustment of the bank morphology was taking place. However, this research lacked detailed investigation of the influence of previous river management practices against which to attribute this adjustment. For example, the impact of channel dredging on marginal vegetation and bank morphology was inferred from old photographs and paintings, rather than from detailed records of dredging activities.

Historical evidence, hydraulic assessment and extensive survey of the banks suggested that the River Thames is generally stable with respect to bank erosion. The extensive data sets generated during this research indicate that, where erosion does occur, it tends to be as a result of a combination of factors, mostly associated with man's use of the river, rather than as a result of adjustment of the channel planform or geometry. Whereas detailed monitoring of river bank processes identified the influence of bank material, geometry and vegetation on the susceptibility of the bank to erosion, only vegetation was surveyed extensively along the Thames. Consequently, whilst the influence of bank material and geometry has not been characterised, the research did highlight the influence of bank vegetation, where 40% of the total length of erosion coincided with unvegetated banks, and the length of erosion decreased as the complexity of bank vegetation increased.

This research has highlighted the complex nature of bank erosion processes, and the difficulties in elucidating the relationship between cause and effect in bio-physical systems and determining the spatial and temporal scales over which processes operate. Nonetheless, this research has characterised the severity of the causes and consequences of erosion along the non-tidal, navigable River Thames and provided a risk-based approach to erosion management which incorporates appropriate measures to mitigate and compensate for environmental degradation.

REFERENCES

Abam, T.K.S. 1993. "Factors affecting the distribution of instability of river banks in the Niger delta", *Engineering Geology*, 35, 123-133.

Ackers, P. and Charlton, F.G. 1970. "Meander geometry arising from varying flows", *Journal of Hydrology*, 11, 230-252.

Alabyan, A.M. and Chalov, R.S. 1998. "Types of river channel patterns and their natural controls", *Earth Surface Processes and Landforms*, 23, 467-474.

Arulanandan, K., Gillogley, E. and Tully, R. 1980. "Development of a quantitative method to predict critical shear stress and rate of erosion of natural undisturbed cohesive soils", Report GL-80-5, US Army Engineers Waterways Experiment Station, Vicksberg, Mississippi.

Ashford, P.L. and Martins, R.M. 1988. "BARS 12A Boat wash study Addendum to BARS 12. A study of the relationship between boat wash and hull form", Broads Authority.

Bass, J.A.B, and Collett, G.D. undated. "Habitat studies in the River Thames: in relation to a Severn-Thames Transfer". Final Report. Environment Agency (Thames Region). IFE Report Ref. No. T04073u7/1.

Bathurst, J.C., Thorne, C.R. and Hey, R.D. 1979. "Secondary flow and shear stress at river bends", *Journal of the Hydraulics Division*, ASCE, 105 (HY10), 1277-1295.

Begin, Z.B. 1987. "Curvature ration and rate of river bend migration - update", *Journal of Hydraulic Engineering*, ASCE, 112, 904-908.

Belloc, H. 1988. *The Historic Thames*. Webb & Bower Ltd., London.

Blake, E. 1993. *Navigation induced bank erosion on the River Yare, with outline proposals for future management*, B.Sc. Thesis, Department of Geography, Nottingham University, Nottingham, UK.

Bonham, A.T. 1980. "Bank protection using emergent plants against boat wash in rivers and canals", Hydraulics Research Station, Wallingford, England. Report No. IT 206.

Bonham, A.J. 1983. "The management of wave-spending vegetation as bank protection against boat wash", *Landscape Planning,* 10, 15-30.

Bowie, A.J. 1982. "Investigations of vegetation for stabilising eroding streambanks", *Transactions ASAE,* 25, 1601-1611.

Bravard, J.-P. and Petts, G.E. 1996. "Human impacts on fluvial hydrosystems", in G.E. Petts and C. Amoros (eds), *Fluvial hydrosystems.* Chapman & Hall. p242-262.

Bridge, J.S. and Jarvis, J. 1977. "Velocity profiles and bed shear stress over various bed configurations in a river bend", *Earth Surface Processes,* 2, 281-294.

Brierley, G.J. and Murn, C.P. 1997. "European impacts on downstream sediment transfer and bank erosion in Cobargo catchment, New South Wales, Australia", *Catena,* 31, 119-136.

Brookes, A. 1988. *Channelized Rivers. Perspectives for environmental management,* John Wiley & Sons Ltd. Chichester.

Brookes, A. 1992. "Recovery and restoration of some engineered British river channels", in P.J. Boon, P. Calow and G.E. Petts (eds), *River conservation and management,* John Wiley & Sons Ltd. Chichester, 337-352.

Brookes, A. 1995. "Challenges and objectives for geomorphology in UK River Management", *Earth Surface Processes and Landforms,* 20, 593-610.

Brookes, A. (ed). 1996. *A "new" approach to river management: the use of geomorphology.* Environment Agency Research and Development National Workshop, Birmingham.

Brookes, A. and Long, H. 1990. "Stort Catchment Morphological Survey: Appraisal Report and Watercourse Summaries", National Rivers Authority, Reading.

Brookes, A., Downs, P. and Skinner, K. (1998) "Uncertainty in the engineering of wildlife habitats", *Journal of the Chartered Institute of Water and Environmental Management,* 12, 25-29.

Brown, A.G. and Keough, M. 1992. "Palaeochannels, palaeoland-surfaces and the tree-dimensional reconstruction of floodplain environmental change", in P.A. Carling and G.E. Petts (eds), *Lowland floodplain rivers: geomorphological perspectives,* John Wiley and Sons Ltd. pp185-202.

Browne, R. 1993. "Repair and protection of vertical pasture banks", River bank workshop held by the River Thames Society, Henley-on-Thames.

BSI 1996. *Implementation of ISO 14001: 1996 Environmental management systems - specification with guidance for use,* British Standards Institute.

Callander, R.A. 1978. "River meandering", *Annual Review of Fluid Mechanics,* 10, 129-158.

Carling, P. 1988. "The concept of dominant discharge applied to two gravel-bed streams in relation to channel stability thresholds, *Earth Surface Processes and Landforms,* 13, 355-367.

Chen, G-X. and Shen, H.W. 1988. "Flow and shear distributions in stream bends", US Army Corps of Engineers, Waterways Experiment Station, Vicksberg. Contract No. DACW39-87-C-0034.

Clark, M.J. 1995. "Information flow for channel management", in A. Gurnell and G. Petts (eds), *Changing river channels,* John Wiley and Sons. pp263-276.

Coppin, N.J. and Richards, I.G. 1990. *Use of vegetation in civil engineering,* CIRIA, Butterworths, London.

Davis, R.J. and Gregory, K.J. 1994. "A new distinct mechanism of river bank erosion in a forested catchment", *Journal of Hydrology,* Vol. 157, 1-11.

Dietrich, W.E. and Smith, J.D. 1983. "Influence of the point bar on flow through curved channels", *Water Resources Research,* 19 (5), 1173-1192.

Downs, P.W. 1995a. "Estimating the probability of river channel adjustment", *Earth Surface Processes and Landforms,* Vol. 20, 687-705.

Downs, P.W. 1995b. "River channel classification for channel management purposes", in A. Gurnell and G. Petts, *Changing river channels,* John Wiley and Sons Ltd., p347-365.

Downs, P.W. and Brookes, A. 1994. "Developing a standard geomorphological approach for the appraisal of river projects", in C. Kirby and W.R. White (eds) *Integrated river basin development,* Wiley, 299-310.

Downs, P.W. and Thorne, C.R. 1996. "A geomorphological justification of river channel reconnaissance surveys", *Transaction of the British Geographical Society NS,* 21, 455-468.

Downward, S.R. 1993. "Hogsmill stream geomorphological evaluation", prepared for the National Rivers Authority, Thames Region.

Downward, S.R. 1995. "Information from topographic survey", in A.Gurnell and G. Petts (eds) *Changing river channels,* John Wiley & Sons Ltd., Chichester, 303-323.

Environment Agency undated a. *Understanding buffer strips - an information booklet.* Bristol.

Environment Agency undated b. *An Environmental strategy for the millennium and beyond.* Bristol.

Environment Agency 1997. "Waterway bank protection: a guide to erosion assessment and management", Environment Agency, British Waterways and Broads Authority, R&D Draft Technical Report W5/i635/3. Prepared by R.P.C. Morgan, A.J. Collins, M.J. Hann, J. Morris, J.A.L. Dunderdale, and D.J.G. Gowing, Silsoe College, Cranfield University, Beds.

Environment Agency 1998a. *National environmental assessment handbook: Environment Agency internal works and activities,* National Centre for Risk Analysis and Options Appraisal, London, Version 1.0.

Environment Agency 1998b. *The Environment Agency's state of the environment report for Thames Region,* Environment Agency, Thames Region, Reading.

Environment Agency 1998c. *LEAP Guidance Version 3* Environment Agency, Bristol.

Environment Agency 1998d. *Thames Environment 21 - The Environment Agency strategy for land-use planning in Thames Region,* Environment Agency, Thames Region, Reading.

Environment Agency 1998e. *Environmental assessment of projects (EA),* Report of the Head of Integrated Environmental Policy, Environment Agency Policy Group, Bristol.

Environment Agency 1998f. *Draft tidal Thames mitigation and compensation policy,* Environment Agency, Thames Region, Reading.

Environment Agency 1998g. *Flood defence conservation requirements for watercourse maintenance works,* Environment Agency, Thames Region, Reading.

Environment Agency 1998h. *Local Environment Agency Plan: Consultation Report for the River Wey,* Environment Agency, Thames Region, Reading.

Environment Agency 1998i. *River Thames Boat Traffic Statistics,* Provided by Environment Agency, Thames Region, Reading.

Ferguson, R.I. 1981. "Channel form and channel changes", in J. Lewin (ed.), *British Rivers,* George Allen and Unwin, London. pp90-125.

Garrad, P.N. and Hey, R.D. 1987. "Boat traffic, sediment resuspension and turbidity in a Broadland river", *Journal of Hydrology,* 95, 289-297.

Garrad, P.N and Hey, R.D. 1988. "The effect of boat traffic on river regime", in W.R. White (ed.), *Proceedings International Conference on River Regime,* John Wiley and Sons Ltd. 395-409.

Gillette, D.A., Herbert, G., Stockton, P.H. and Owen, P.R. 1996. "Causes of the fetch effect in wind erosion", *Earth Surface Processes and Landforms,* 21, 641-659.

Glynn, J., Hills, K., Appleton, S., Reid, K. and Vamadeven, N. 1994. *Suggested designs: river bank protection and other minor works,* National Rivers Authority, Thames Region, Reading.

Goodwin, T. 1995. *Experimental and alternative methods of bank protection,* National Rivers Authority, Anglian Region, Norwich.

Gregory, K.J. 1992. "Vegetation and river channel process interactions", in P.J. Boon, P. Calow and G.E. Petts (eds), *River Conservation and Management,* John Wiley and Sons Ltd. Chichester, 255-270.

Grissinger, E.H. 1982. "Bank erosion of cohesive materials", in R.D. Hey, J.C. Bathurst, and C.R. Thorne (eds), *Gravel-bed rivers,* John Wiley and Sons Ltd. pp273-287.

Gurnell, A.M. 1995. "Vegetation along river corridors: hydrogeomorphological interactions", in A. Gurnell and G. Petts (eds), *Changing river channels,* John Wiley and Sons. pp237-260.

Hagerty, D.J. and Hagerty, M.J. 1989. "Ohio River bank erosion - traffic effects", *Journal of Waterway, Port, Coastal and Ocean Engineering,* 115, 404-408.

Hagerty, D.J., Spoor, M.F. and Ullrich, C.R. 1981. "Bank failure and erosion on the Ohio River", *Engineering Geology,* 17, 141-158.

Haltiner, J.P., Kondolf, G.M. and Williams, P.B. 1996. "Restoration approaches in California", in A. Brookes and F.D. Shields Jr. (eds) *River channel restoration,* John Wiley & Sons Ltd., p291-329.

Harper, D., Smith, C, Barham, P. and Howell, R. 1995. "The ecological basis for the management of the natural river environment", in D.M. Harper and A.J.D. Ferguson (eds), *The ecological basis for river management*, John Wiley and Sons Ltd. Chichester. 219-238.

Hemphill, R.W. and Bramley, M.E. 1989. *Protection of river and canal banks: a guide to selection and design*, CIRIA Water Engineering Report, Butterworths.

Hey, R.D., Heritage, G.L., Tovey, N.K., Boar, R.R., Grant, A. and Turner, R.K. 1991. "Streambank protection in England and Wales", R&D Note 22, National Rivers Authority, London.

Hicks, F.E., Jin, Y.C. and Steffler, P.M. 1990. "Flow near sloped bank in curved channel", *Journal of Hydraulic Engineering*, 116, 55-70.

HMSO 1988. *The Land Drainage Improvement Works (Assessment of Environmental Effects) Regulations 1988*, Statutory Instrument No. 1217, HMSO, London.

HMSO 1991. *The Water Resources Act 1991* HMSO, London.

HMSO 1995. *The Environment Act 1995* HMSO, London.

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

Hooke, J. M. 1980. Magnitude and distribution of rates of river bank erosion. *Earth Surface Processes*, 5, 143-157.

Hooke, J.M. 1995. "Processes of channel planform change on meandering channels in the UK", in A. Gurnell and G. Petts (eds), *Changing river channels*, John Wiley and Sons. pp87-115.

Hooke, J.M. and Harvey, A.M. 1983. "Meander changes in relation to bend morphology and secondary flow", *International Association of Sedimentologists Special Publication*, 6, 121-132.

Hooke, J.M. and Redmond, C. E. 1989. "Use of cartographic sources for analysing river channel change with examples from Britain", in G.E. Petts (ed) *Historical Change of Large alluvial Rivers: western Europe,* John Wiley & Sons Ltd., pp 79-93.

Hooke, J.M., Harvey, A.M., Miller, S.Y. and Redmond, C.E. 1990. "The chronology and stratigraphy of the alluvial terraces of the River Dane valley, Cheshire, N.W. England", *Earth Surface Processes and Landforms,* 15, 717-737.

Hooke, R. Le B. 1975. "Distribution of sediment transport and shear stress in a meander bend", *Journal of Geology,* 83 (5), 543-565.

Hugget, D. 1998. "The management of coastal flood defences, no net loss - mitigation banking and biodiversity", Royal Society for the Protection of Birds, Sandy, Bedfordshire.

Kirkby, M.J. and Morgan, R.P.C. 1980. *Soil erosion,* John Wiley and Sons, Chichester.

Knighton, D. 1984. *Fluvial forms and processes.* Edward Arnold (Publishers) Ltd.

Kobayashi, N., Raichle, A.W. and Asano, T. 1993. "Wave attenuation by vegetation", *Journal of Waterway, Port, Coastal, and Ocean Engineering,* 119, 30-48.

Kondolf, G.M. and Downs, P.W. 1996. "Catchment approach to planning channel restoration", in A. Brookes and F.D. Shields Jr. (eds) *River channel restoration,* John Wiley & Sons Ltd., p130-148.

Lapoint, M.K. and Carson, M.A. 1986. "Migration of an asymmetric meandering river: the Rouge River, Quebec", *Water Resources Research,* 22 (5), 731-743.

Lawler, D.M. 1992. "Process dominance in bank erosion systems", in P.A. Carling and G.E. Petts (eds), *Lowland floodplain rivers: geomorphological perspectives,* John Wiley and Sons. pp117-143.

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

Lawler, D.M. 1993b. "Needle ice process and sediment mobilisation on river banks: the River Ilston, West Glamorgan, UK", *Journal of Hydrology*, 150, 81-114.

Lawler, D.M., Thorne, C.R and Hooke, J.M. 1997. "Bank erosion and stability", in C.R. Thorne, R.D. Hey and M.D. Newson (eds), *Applied fluvial geomorphology for river engineering and management*, John Wiley & Sons Ltd. pp137-172.

Leopold, L.B., Wolman, M.G. and Miller, J.B. 1964. *Fluvial processes in geomorphology*. W.H. Freeman, San Francisco.

Macklin, M.G. and Lewin, J. 1997. "Channel, floodplain and drainage basin response to environmental change", in C.R. Thorne, R.D. Hey and M.D. Newson (eds), *Applied fluvial geomorphology for river engineering and management*, John Wiley & Sons Ltd. pp15-45.

MAFF/WO 1996. *Code of practice on environmental procedures for flood defence operating authorities*, Ministry of Agriculture, Fisheries and Food and The Welsh Office.

Masterman, R. and Thorne, C.R. 1992. "Predicting the influence of bank vegetation on channel capacity", *Journal of Hydraulic Engineering*, ASCE, 118, 1052-1058.

May, R.W.P. and Waters, C.B. 1986. "BARS 12 Boat wash study April/May 1986", Broads Authority, Report No. EX 1476.

Mazumder, B.S., Bhowmik, N.G. and Soong, T.W. 1993. "Turbulence in rivers due to navigation traffic", *Journal of Hydraulic Engineering*, 119, 581-597.

Millar, R.G. and Quick, M.C. 1993. "Effect of bank stability on geometry of gravel bed rivers", *Journal of Hydraulic Engineering*, 119, 1343-1363.

Murgatroyd, A.L. and Ternan, J.L. 1983. "The impact of afforestation on stream bank erosion and channel form", *Earth Surface Processes and Landforms,* 8, 357-369.

Newson, M.D. 1980. "The erosion of drainage ditches and its effect on bedload yields in mid-Wales: reconnaissance case studies", *Earth Surface Processes and Landforms,* 8, 357-369.

Newson, M.D. 1994. *Hydrology in the river environment.* Clarendon Press, Oxford.

Newson, M.D. and Sear, D. 1998. "The role of geomorphology in monitoring and managing river sediment systems", *Journal of the Chartered institute of Water and Environmental Management,* 12, 18-24.

Newson, M.D., Hey, R.D., Bathurst, J.C., Brookes, A., Carling, P.A., Petts, G.E. and Sear, D.A. 1997. "Case studies in the application of geomorphology to river management", in C.R. Thorne, R.D. Hey, and M.D. Newson (eds), *Applied fluvial geomorphology for river engineering and management,* John Wiley and Sons, 311-363.

Nicholson/Ordnance Survey 1990. *Guide to the River Thames.*

NRA undated a. *River Thames Handbook.* National Rivers Authority, Thames Region, Public Relations.

NRA undated b. *An investigation into the use of bio-technology in river management,* National Rivers Authority Thames Region.

NRA undated c. *Fact Files: Upper, Middle and Lower River Thames.* National Rivers Authority, Thames Region.

NRA 1991. "Bank erosion on navigable waterways", R&D Project Report 225/1/T. National Rivers Authority, Bristol. Prepared by J.M. Hooke, D.H. Bayliss and N.J. Clifford, Southampton University.

NRA 1992. *Thames Environment Design Handbook,* National Rivers Authority, Thames Region, Reading.

NRA 1993. *Thames 1:10,000 map atlas of bank erosion and protection,* Prepared by Nottingham University for the Geomorphology Section, Fisheries and Conservation. National Rivers Authority, Thames Region, Reading.

NRA 1994a. *Thames Region Environmental Assessment Procedures.* National Rivers Authority, Thames Region, Reading. Draft, April 1994.

NRA 1994b. "Riverbank erosion and solutions", R&D Project Record 336/3/T, National Rivers Authority, Bristol. Prepared by S. Reed, C.R. Thorne and J.C. Doornkamp, Nottingham University.

NRA 1994c. 1994. "River bank erosion problems. Recommendations for their management in the NRA", R&D Note 204, National Rivers Authority, Bristol.Prepared by J.C. Doornkamp, C.R. Thorne and S. Reed, Nottingham University.

NRA 1995. *Irish Bridge: River Liza, Cumbria. Fluvial Audit,* Report by S. Reed, Geomorphology Section, National Rivers Authority, Reading.

NRA 1996. "A procedure for assessing river bank erosion problems and solutions", R&D Report 28, National Rivers Authority, Bristol. Prepared by C.R. Thorne, S. Reed and J.C. Doornkamp, Nottingham University.

Odgaard, A.J. 1982. Bed characteristics in alluvial channel bends. *Journal of the Hydraulics Division,* ASCE, 108 (HY11), 1268-1281.

Odgaard, A.J. 1987. "Streambank erosion along two rivers in Iowa", *Water Resources Research,* 23 (7), 1225-1236.

Odgaard, A.J. and Mergs, M.A. 1988. "Flow processes in a curved alluvial channel", *Water Resources Research,* 24 (1), 45-56.

Okagbue, C.O. and Abam, T.K.S. 1986. "An analysis of stratigraphic control on river bank failure" *Engineering Geology,* 22, 231-245.

Parsons, D.A. 1963. "Vegetative control of streambank erosion". Paper No. 20 USDA Misc. Publ. 970, 130-136.

Payne, S.J. and Hey, R.D. 1982. "BARS 4 River management to reduce bank erosion. Yare and Bure River system", Broads Authority, Norwich.

Petts, G.E. 1977. "Channel response to flow regulation: the case of the River Derwent, Derbyshire", in K.J. Gregory (ed.), *River Channel Changes*, John Wiley and Sons Ltd. pp145-163.

Petts, G. E., Armitage, P. and Castella, E. 1993. "Physical habitat changes and macro-invertebrate response to river regulation: the River Rede, UK", *Regulated Rivers: Research and Management*, 8, 167-178.

PIANC 1987. "Guidelines for the design and construction of flexible revetments incorporating geotextiles for inland waterways", Report of Working Group 4 of the Permanent Technical Committee. Supplement to Bulletin No. 57. Brussels.

Piégay H., Cuaz, M., Javelle, E. and Mandier, P. 1997. "Bank erosion management based on geomorphological, ecological and economic criteria on the Galaure River, France", *Regulated Rivers: Research and Management*, 13, 433-448.

Pizzuto, J. 1986. "Flow variability and the bankfull depth of sand-bed streams of the american midwest", *Earth Surface Processes and Landforms*, 11, 441-450.

Pizzuto, J.E. and Meckelnburg, T.S. 1989. "Evaluation of a linear bank erosion equation", *Water Resources Research*, 25 (5) 1005-1013.

Reed, S. 1990. "The characterisation and estimation of outer bank velocities in meander bends" B.Sc. Thesis, Queen Mary and Westfield College, University of London. Research undertaken for the US Army Corps of Engineers Waterways Experiment Station, Vicksberg.

Rhoads, B.L. and Kenworthy, S.T. 1998. "Time-averaged flow structure in the Central Rec a stream confluence", *Earth Surface Processes and Landforms*, 23, 171-191.

Richards, K.S. 1976. "The morphology of riffle-pool sequences", *Earth Surface Processes*, 1, 71-88.

Richards, K. 1982. *River channel form and process*. Methuen, London.

Risbey, J.S. and Entekhabi, D. 1996. "Observed Sacramento River basin streamflow response to precipitation and temperature changes and its relevance to climate impact studies", *Journal of Hydrology*, 184, 209-223.

RSPB/NRA/RSNC 1984. *Rivers and wildlife handbook: A guide to practices which further the conservation of wildlife on rivers*. Lewis, G. and Williams, G., RSPB, NRA and RSNC.

RSPB/NRA/RSNC 1994. *The new rivers and wildlife handbook: A guide to practices which further the conservation of wildlife on rivers*. RSPB, NRA and RSNC.

Rumsby, B.T and Macklin, M.G. 1994. "Channel and floodplain response to recent abrupt climate change: the Tyne basin, Northern England", *Earth Surface Processes and Landforms*, 19, 499-515.

Schiechtl, H.M. and Stern, R. 1997. "Water Bioengineering Techniques for Watercourses, Bank and Shoreline Protection". Translated by L Jaklitsch. UK Editor D. H. Barker, Blackwell Science Ltd.

Schumm, S.A. 1977. *The fluvial system*,Wiley, New York.

Sear, D.A. 1992. "Mimmshall Brook: geomorphological assessment", unpublished report to National Rivers Authority, Thames Region, Reading.

Sear, D.A. 1996. "The sediment system and channel stability", in A. Brookes and F.D. Shields Jr. (eds) *River channel restoration*, John Wiley & Sons Ltd., p149-177.

Sear, D.A., Darby, S.E., Thorne, C.R. and Brookes, A. 1994. "Geomorphological approach to stream stabilization and restoration: a case study of the Mimmshall Brook, Hertfordshire, UK", *Regulated Rivers: Research and Management*, 9, 205-223.

Simon, A. 1989. "A model of channel response in disturbed alluvial channels", *Earth Surface Processes and Landforms,* 114, 11-26.

Simons, D.B. and Li, R-M. 1982. "Bank erosion on regulated rivers", in R.D. Hey, J.C. Bathurst and C.R. Thorne (eds), *Gravel bed rivers,* John Wiley and Sons Ltd., Chichester. pp717-754.

Simons, D.B. and Richardson, E.V. 1966. "Resistance to flow in alluvial channels", *United States Geological Survey Professional Paper,* 422J, 61pp.

Smith, B.J. 1998. Paper to Willows Workshop hosted by Middlesex University.

Smith, B.J. 1994. "The Medway River Project: an example of community participation in integrated river management", in C. Kirby and W.R. White (eds) *Integrated river basin development,* Wiley, 377-387.

Smith, C.D., Harper, D.M. and Barham, P.J. 1990. "Engineering operations and invertebrates: linking hydrology with ecology", *Regulated Rivers: Research and Management,* 5, 89-96.

Smith, G. 1998. "Overview of EA process and recent developments in EC legislation", Paper presented on behalf of the Department of Environment, Transport and the Regions at *Mitigating environmental impacts: practical examples from construction and industry,* CIWEM Technical Conference, 3 April, London.

Springer, Jr., F.M., Ullrich, C.R. and D.J. Hagerty. 1985. "Streambank stability", *Journal of Geotechnical Engineering,* 111, 624-640.

Stott, T. 1997. "A comparison of stream bank erosion processes on forested and moorland streams in the Balquhidder catchments, central Scotland", *Earth Surface Processes and Landforms,* 22, 383-399.

Swales, S. "Environmental effects of river channel works used in land drainage improvement", *Journal of Environmental Management,* 14, 103-126.

Taylor, M.P. and Lewin, J. 1996. "River behaviour and Holocene alluviation: the River Severn at Welshpool, Mid-Wales, UK", *Earth Surface Processes and Landforms*, 21, 77-91.

Thames Conservancy 1965. "Statistics of rainfall, flow and levels of the River Thames above Teddington for 82 years, 1883-1964 Volume I", Chief Engineer's Department, Reading. Harrison and Sons, Ltd. London.

Thames Water 1987. *River Thames Model Stage One. Submodel: Marlow to Old Windsor.* Prepared by Sir William Halcrow and Partners Ltd.

Thames Water 1988a. *River Thames Model Stage One. Submodel: Old Windsor to Teddington.* Prepared by Sir William Halcrow and Partners Ltd.

Thames Water 1988b. *River Thames Model Stage One. Submodel: Days to Marlow.* Prepared by Sir William Halcrow and Partners Ltd.

Thames Water 1988c. *River Thames Model Stage One. Submodel: St.Johns to Eynsham.* Prepared by Sir William Halcrow and Partners Ltd.

Thames Water 1988d. *River Thames Model Stage One. Submodel: Eynsham to Days.* Prepared by Sir William Halcrow and Partners Ltd.

Thompson, A. 1986. "Secondary flows and the pool-riffle unit: a case study of the processes of meander development", *Earth Surface Processes and Landforms,* 11, 631-641.

Thoms, M.C. and Walker, K.F. 1992. "Channel changes related to low-level weirs on the River Murray, South Australia", in P.A. Carling and G.E. Petts (eds), *Lowland floodplain rivers: geomorphological perspectives,* John Wiley and Sons. pp235-249.

Thoms, M.C. and Walker, K.F. 1993. "Channel changes associated with two adjacent weirs on a regulated lowland alluvial river", *Regulated Rivers: Research and Management,* 8, 271-284.

Thorne, C.R. 1982. "Process and mechanisms of river bank erosion", in R.D. Hey, J.C. Bathurst and C.R. Thorne (eds), *Gravel bed rivers,* John Wiley and Sons Ltd., Chichester. pp227-271.

Thorne, C.R. 1990. "Effects of vegetation on riverbank erosion and stability", in J.B. Thornes (ed.), *Vegetation and erosion,* John Wiley and Sons Ltd. pp125-144.

Thorne, C.R. 1991. "Bank erosion and meander migration of the Red and Mississippi Rivers, USA", in *Hydrology for the Water Management of Large River Basins,* Proceedings of the Vienna Symposium, August 1991, IAHS Publ. no. 201.

Thorne, C.R. 1992a. "Field assessment techniques for bank erosion modelling", Final Report to US Army European Research Office, London, England. Research Contract No. R&D 6560-EN-09.

Thorne, C.R. 1992b. "Bend scour and bank erosion on the meandering Red River, Louisiana", in P.A. Carling and G.E. Petts (eds), *Lowland floodplain rivers: geomorphological perspectives,* John Wiley and Sons. p95-115.

Thorne, C.R. 1997. "Channel types and morphological classification", in C.R. Thorne, R.D. Hey, and M.D. Newson (eds), *Applied fluvial geomorphology for river engineering and management,* John Wiley and Sons, p175-222.

Thorne, C.R. and Hey, R.D. 1979. "Direct measurement of secondary currents at a river inflexion point", *Nature,* 280, 226-228.

Thorne, C.R. and Lewin, J. 1979. "Bank processes, bed material movement and planform development in a meandering river", in D.D. Rhoes and G.P.Williams (eds), *Adjustment to the fluvial system.* Kendall Hunt, Dubuque, IA, p117-137.

Thorne, C.R., Newson, M.D., and Hey, R.D. 1997. "Application of applied fluvial geomorphology: problems and potential", in C.R. Thorne, R.D. Hey, and M.D. Newson (eds), *Applied fluvial geomorphology for river engineering and management,* John Wiley and Sons, 365-370.

Thorne, C.R. and Osman, A.M. 1988. "The influence of bank stability on regime geometry of natural channels", in White, W.R. (ed), *International Conference on River Regime*. Hydraulics Research Ltd./John Wiley and Sons, Chichester. p135-147.

Thorne, C.R. and Tovey, N.K. 1981. "Stability of composite river banks", *Earth Surface Processes and Landforms*, 6, 469-484.

Trimble, S.W. 1988. "The impact of organisms on overall erosion rates within catchments in temperate regions", in H.A. Viles (ed.), *Biogeomorphology*, Blackwell, Oxford. pp83-142.

Trimble, S.W. 1994. "Erosional effects of cattle on streambanks in Tennessee, USA", *Earth Surface Processes and Landforms*, 19, 451-464.

USACE 1990. "Re-evaluation of the stream bank erosion control evaluation and demonstration project", US Army Corps of Engineers Project No. 76-406-89, Draft Report by Water Engineering and Technology, Inc., Colorado.

Van Alphen, J.S.L.J., Bloks, P.M. and Hoekstra, P. 1984. "Flow and grain size pattern in a sharply curved river bend", *Earth Surface Processes and Landforms*, 9, 513-522.

Vanoni, V.A and Nomicos, G.N. 1960. "Resistance properties of sediment-laden streams:, *Transactions of the American Society of Civil Engineers*, 125, 1140-1167.

Vincent, C.E. 1988. "BARS 12B Boat wash study Addendum to BARS 12. A Comparison of wind-generated waves and boat generated waves on Broadland Rivers", Broads Authority.

Whiting, P.J. 1997. "The effect of stage on flow and components of the local force balance", *Earth Surface Processes and Landforms*, 22, 517-530.

Whitlow, J.R. and Gregory, K.J. 1989. "Changes in urban stream channels in Zimbabwe", *Regulated Rivers: Research and Management*, 4, 27-42.

Wolfe, W.J. and Bryan, B.A. 1991. "Drought-related West Tennessee channel and bank failures", *Proceedings from the ASCE 1991 National Conference on Hydraulic Engineering.*

Woolhouse, C. 1994. "Catchment management plans: current successes and future opportunities", in C. Kirby and W.R. White (eds) *Integrated river basin development,* Wiley, 463-474.

World Bank. 1995. *Monitoring environmental progress: a report of work in progress,* Environmentally Sustainable Development Series, Washington, DC, USA.

APPENDICES

Appendix 1 The River Thames catchment and political boundaries.

1.1 The River Thames catchment.

1.2 Thames Region and its political boundaries.

Appendix 2 The River Thames Bank Survey.

2.1 Parameters recorded in the River Thames Bank Survey.

Appendix 3 Derivation of the River Thames reach characteristics.

3.1 Example output from the Thames hydraulic model (Thames Water, 1988c) illustrating the surface water slope along Grafton Reach.

3.2 Extract from the Geological Survey of Great Britain (1:50,000 series) Map 268 showing the alluvial floodplain and comtemporary valley axis along Sonning Reach.

Appendix 4 River Thames bank erosion monitoring.

4.1 Location and details of each erosion monitoring site.

4.2 Bank erosion measured at each monitoring site.

4.3 Bank shear strength and soil suction measured at each monitoring site.

4.4 Surveys of bank profiles taken at each monitoring site.

4.5 Hydrometric data for the erosion monitoring sites.

4.6 Boat traffic data for the erosion monitoring sites.

Appendix 5 River Thames reach characteristics.

5.1 Channel geometry and discharge data for each reach of the River Thames.

5.2 Bank protection and vegetation characteristics for each reach of the River Thames.

5.3 Boat wash monitoring and bank shear stress data.

5.4 Factors contributing to erosion at 147 sites along the River Thames.

Appendix 6 **River bank erosion control strategies**

- **6.1** **Decision tree for selection of erosion control strategy (from Environment Agency, 1997).**
- **6.2** **Decision trees for selection of erosion control techniques (from Environment Agency, 1997).**
- **6.3** **List of erosion control techniques on non-River Thames sites reviewed by the author during Phase II of the NRA/Environment Agency's R&D project (from NRA, 1994b).**
- **6.4** **Details of erosion control case studies on the River Thames.**
- **6.5** **Performance review of erosion control case studies on the River Thames.**

Appendix 7 **Examples of bank erosion control techniques for use along the River Thames.**

APPENDIX 1

Appendix 1.1

The River Thames catchment

Courtesy of the Environment Agency, Thames Region

Appendix 1.2

The River Thames catchment showing political boundaries

Courtesy of the Environment Agency, Thames Region

APPENDIX 2

Appendix 2.1

Parameters recorded in the River Thames Bank Survey (Volume II).

The following parameters were recorded on the 1:10,000 scale map atlas, the River Thames Bank Survey, presented as Volume II of this thesis. The reach-scale assessments reported in this research collated data relating to the banks along each reach of the Thames, i.e. from lock to lock and from weir to weir (see Maps in Volume III).

Note: * denotes parameters measured for the erosion assessment.

<u>Bank characteristics</u>:

Length of bank protected with (intact and failing):
- sheet piling*
- concrete bagwork*
- concrete or masonry*
- brickwork*

Length of bank with (intact and failing) 'soft' bank protection:
- gabion baskets*
- geotextiles*
- spiling*

Length of protected bank with:
- no vegetation (i.e. hard-standing)*

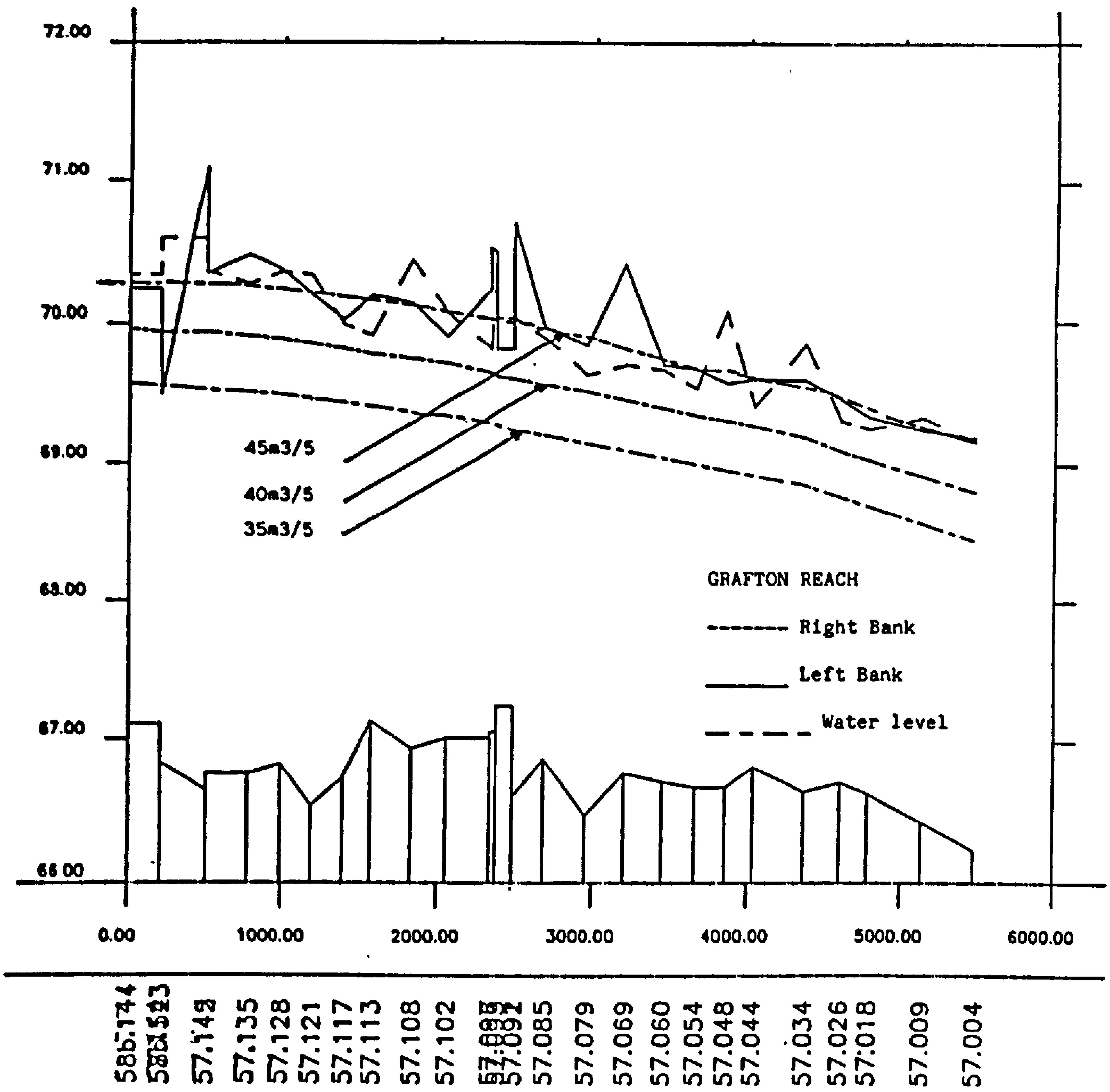
Length of unprotected bank with particular vegetation characteristics:
- no vegetation (i.e. bare earth bank)*
- grass*
- shrubs*
- sparse trees*
- wooded*

Marginal reeds
Eroding bankline*
Beach profile and stabilising beach profile

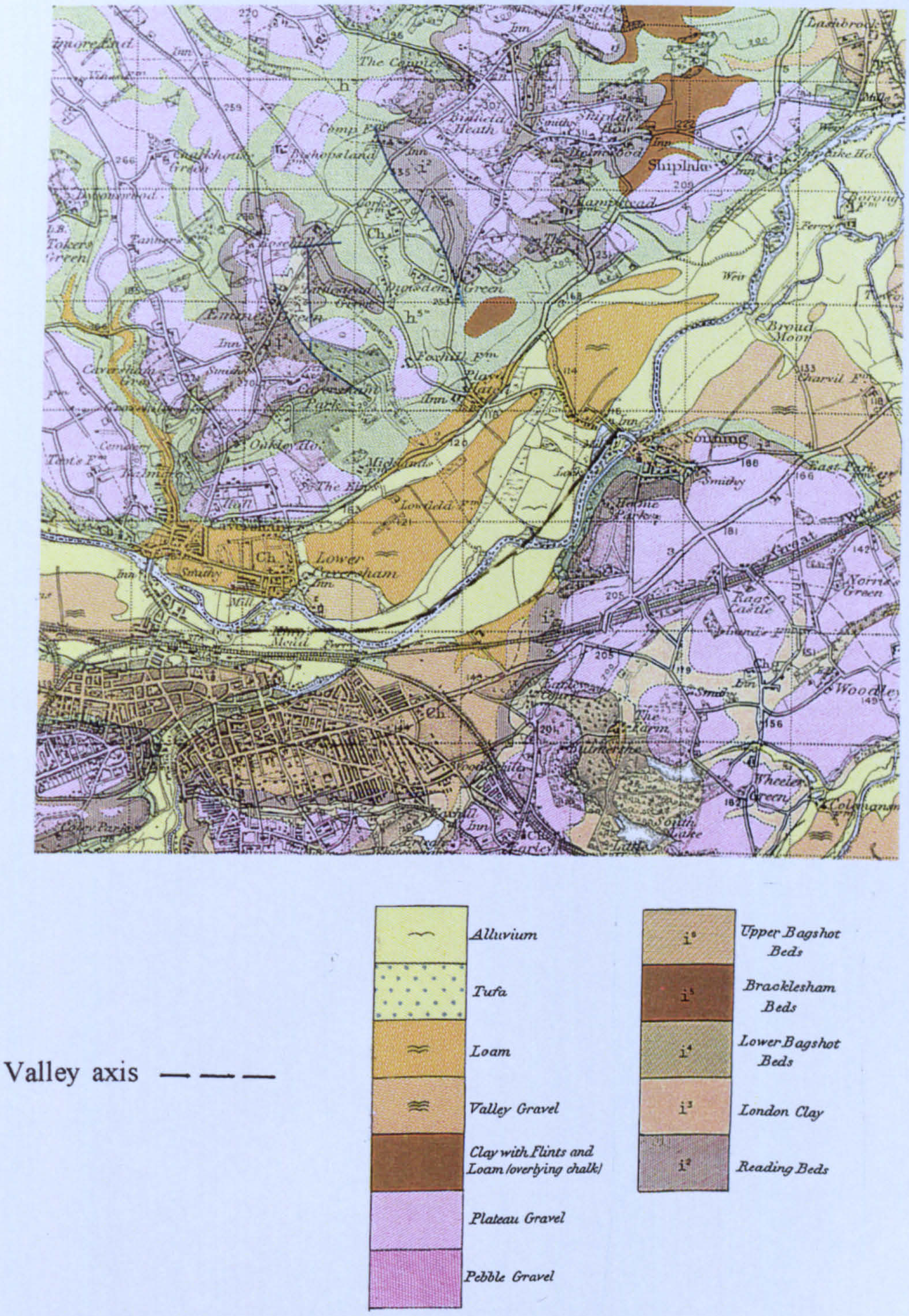
Channel and bank use:
- grazing and livestock access points
- angling and wooden fishing embankments
- designated mooring sites, mooring platforms, boat yards and landing stages

APPENDIX 3

Appendix 3.1 Example output from the Thames hydraulic model (Thames Water, 1988c) illustrating the surface water slope along Grafton Reach.



Appendix 3.2 Extract from the Geological Survey of Great Britain (1:50,000 series) Map 268 showing the alluvial floodplain and contemporary valley axis along Sonning Reach.



APPENDIX 4

Appendix 4.1 Details of bank erosion monitoring sites

	St. Johns	Upper Wallingford	Lower Wallingford	Goring	Laleham	Upper Chertsey	Lower Chertsey
Site location and details:							
Grid reference	422198	461189	461189	459180/181	505167	505166	505166
OS 1: 50,000 map	163	175	175	174	176	176	176
OS 1:10,000 map	SU 29 NW	SU 68 NW	SU 68 NW	SU 58 SE	TQ 06 NE	TQ 06 NE	TQ 06 NE
Left/right bank (LB/RB)	RB	RB	LB	RB	LB	LB	LB
Length of site (m)	20	253	160	-	15	15	44
No. of bank profiles surveyed	5	6	8	3	0	4	6
No. of bank profiles with erosion pins installed	1	3	8	1*	1*	4	3
Total no. of erosion pins originally installed	2	6	16	2	2	8	6
Dates of bank surveys:							
Initial survey date	10-Mar-92	24-Jan-92	3-Jan-92	24-Jan-92	N/A	28-Jul-92	5-Mar-92
Second survey date	6-Jul-92	6-Jul-92	16-Jun-92	6-Jul-92	N/A	29-Oct-92	8-Jul-92
Third survey date	1-Nov-92	30-Oct-92	30-Oct-92	1-Nov-92	N/A	N/A	29-Oct-92
Final survey date	3-Feb-93	2-Feb-93	2-Feb-93	2-Feb-93	N/A	11-Jan-93	11-Jan-93
Analysis of soil samples:							
Date of soil sampling	6-Jul-92	9-Aug-92	9-Aug-92	6-Jul-92	29-Oct-92	29-Oct-92	29-Oct-92
Compressive strength (N/sq mm)	0.116	0.472	0.068	0.118	0.044	0.072	0.012
Tensile strength (N/sq mm)	0.09	0.018	0.015	0.015	0.013	0.015	0.013
Bulk density (g/cubic cm)	1.596	2.481	5.104	1.501	1.698	2.263	1.847
Moisture (%)	33.05	21.79	16.11	34.97	23.59	20.23	20.8
Organic matter (%)	0.94	4.11	12.9	13.58	7.65	9.01	5.92
Sand (%)	18.67	39.2	43.43	19.69	35.45	48.28	43.94
Silt + clay (%)	47.34	34.9	27.56	31.76	33.31	22.48	29.34
Description of bank:							
General description of bank material (cohesive, non-cohesive, composite)	Cohesive	Composite/ cohesive	Composite/ cohesive	Cohesive	Thin cohesive root mat & sandy toe	Cohesive upper bank, clay toe	Composite
- Upper bank	Cohesive	Cohesive (gravelly)	Cohesive (gravelly)	Cohesive	Cohesive	Cohesive	Cohesive
- Lower bank	Cohesive	Clay	Clay (with non-cohesive sand at toe)	Cohesive	Sandy toe	Sandy with clay toe	Cohesive (gravelly)
Location/extent of tension cracks	Confined to soil surface	Limited to unvegetated upper bank	Limited to unvegetated upper bank	None	None	Limited to unvegetated upper bank	Limited to unvegetated upper bank
Bank height	Low	High	High	Low	Low	High	High
Slope of bank	Sloping	Steep	Steep (verticle)	Steep (verticle)	Sloping	Steep, sloping in places	Steep, sloping in places
Spending beach	No	No	Sandy	No	Sandy	Sandy, with pebbles	Pebble
Bank vegetation	Grass with reeds	Grass, shrubs & some trees	Managed Grass	Grass	Managed Grass	Grass	Grass
Channel and bank use:							
Mooring	No Mooring	Mooring	Mooring	Mooring	No Mooring	No Mooring	No Mooring
Angling	Angling	Angling	Angling	Angling	Angling	Angling	Angling
Recreation/amenity	Walking	Footpath	Footpath	Footpath	Picnic Area	Footpath	Footpath
Grazing	Cattle	No Grazing	No Grazing	Few cattle	Fowl	Cattle	Cattle

Note: * erosion pins were not installed at surveyed bank profiles

Appendix 4.1 Location and site plan (not to scale) of erosion monitoring sites

Appendix 4.2 Bank erosion measured at each monitoring site

		Bank erosion measured as the length of erosion pin exposure (mm) since the previous visit												Total and average values for each erosion pin				Total and average values for the upper and lower erosion pins for each site		
														Total erosion (mm)	Monitoring period (years)	Erosion rate (mm/yr)	Erosion rate (m/yr)	Bank	Total erosion (mm)	Average rate of erosion (m/yr)
St.John's		**10-Mar-92**	**13-Apr-92**	**10-May-92**	**16-Jun-92**	**21-Jul-92**	**24-Aug-92**	**29-Sep-92**	**1-Nov-92**	**3-Feb-93**										
Profile 2	Upper pin	Installed	0	9	0	0	RP (85)	0	15	0				24 (109)	1.17	20.5 (93)	0.021 (0.093)	**Upper bank:**	**109**	**0.021 (0.093)**
Profile 2	Lower pin	Installed	20	11	21	0	RP (150)	100	50	13				215 (365)	1.17	183.7 (312)	0.184 (0.312)	**Lower bank:**	**365**	**0.184 (0.312)**
Upper Wallingford		**24-Jan-92**	**6-Feb-92**	**9-Mar-92**	**13-Apr-92**	**11-May-92**	**16-Jun-92**	**20-Jul-92**	**24-Aug-92**	**28-Sep-92**	**30-Oct-92**	**2-Feb-93**	**9-May-93**							
Profile 4	Upper pin	Installed	41	7	2	2	0	0	0	HF	71	52	8	183	1.29	141.860	0.142	**Upper bank:**	**217**	**0.066**
Profile 4	Lower pin	Installed	0	24	34	54	0	39	29	HF	100	Deposition	80	340	1.29	263.568	0.264	**Lower bank:**	**662**	**0.148**
Profile 5	Upper pin		Installed	0	0	0	0	0	0	HF	0	30	Vegetation	30	1.24	24.194	0.024			
Profile 5	Lower pin		Installed	106	19	4	30	0	0	HF	HF	Deposition	Vegetation	159	1.24	128.226	0.128			
Profile 6	Upper pin		Installed	0	0	0	0	0	0	HF	0	0	4	4	1.24	3.226	0.003			
Profile 6	Lower pin		Installed	2	0	2	39	0	0	HF	6	10	4	63	1.24	50.806	0.051			
Lower Wallingford		**3-Jan-92**	**6-Feb-92**	**9-Mar-92**	**13-Apr-92**	**11-May-92**	**16-Jun-92**	**20-Jul-92**	**24-Aug-92**	**28-Sep-92**	**30-Oct-92**	**2-Feb-93**	**9-May-93**							
Profile 1	Upper pin	Installed	2	28	0	0	0	0	0	40	0	48	9	125	1.35	92.593	0.093	**Upper bank:**	**1696**	**0.157**
Profile 1	Lower pin	Installed	25	0	0	14	0	0	81	HF	27	0	20	167	1.35	123.704	0.124	**Lower bank:**	**1721**	**0.122 (0.160)**
Profile 2	Upper pin	Installed	4	0	0	0	3	3	30	HF	3	0	30	73	1.35	54.074	0.054			
Profile 2	Lower pin	Installed	10	5	24	31	4	0	16	HF	55	75	0	220	1.35	162.963	0.163			
Profile 3	Upper pin	Installed	51	0	12	5	4	0	0	HF	32	48	M	152	1.35	112.593	0.113			
Profile 3	Lower pin	Installed	21	0	45	4	20	8	17	HF	40	HF	M (100)	155 (255)	1.35	114.8 (188.9)	0.115 (0.189)			
Profile 4	Upper pin	Installed	0	37	14	12	31	168	0	HF	60	4	0	326	1.35	241.481	0.241			
Profile 4	Lower pin	Installed	89	127	128	RP (50)	RP (50)	0	RP (100)	HF	RP (100)	130	51	525 (825)	1.35	388 (611)	0.388 (0.611)			
Profile 5	Upper pin	Installed	0	161	9	9	30	12	85	HF	0	10	75	391	1.35	289.630	0.290			
Profile 5	Lower pin	Installed	20	6	0	0	0	9	8	HF	14	13	20	90	1.35	66.667	0.067			
Profile 6	Upper pin	Installed	2	2	2	0	32	25	74	HF	34	35	15	221	1.35	163.704	0.164			
Profile 6	Lower pin	Installed	0	7	0	6	13	19	0	HF	2	HF	10	57	1.35	42.222	0.042			
Profile 7	Upper pin	Installed	8	8	0	19	1	0	25	HF	56	18	5	140	1.35	103.704	0.104			
Profile 7	Lower pin	Installed	0	4	0	5	28	7	0	HF	HF	HF	35	79	1.35	58.519	0.059			
Profile 8	Upper pin	Installed	0	38	49	17	0	0	0	3	0	110	50	267	1.35	197.778	0.198			
Profile 8	Lower pin	Installed	6	3	0	0	4	0	0	3	RP	12	M	28	1.35	20.741	0.021			
Goring		**24-Jan-92**	**9-Mar-92**	**13-Apr-92**	**10-May-92**	**16-Jun-92**	**6-Jul-92**	**23-Aug-92**	**28-Sep-92**	**1-Nov-92**	**2-Feb-93**	**9-May-93**								
	Upper pin	Installed	15	9	5	1	RP	0	0	8	23	4		65	1.29	50.388	0.050	**Upper bank:**	**66**	**0.050**
	Lower pin	Installed	52	0	0	0	RP	10	0	3	M	5		70	1.29	54.264	0.054	**Lower bank:**	**70**	**0.054**
Laleham		**6-Mar-92**	**14-Apr-92**	**10-May-92**	**14-Jun-92**	**20-Jul-92**	**23-Aug-92**	**27-Sep-92**	**29-Oct-92**	**9-May-93**										
	Upper pin	Installed	9	0	0	0	0	0	0	Eroded (500)				9 (509)	1.18	7.6 (431)	0.007 (0.431)	**Upper bank:**	**509**	**0.007 (0.431)**
	Lower pin	Installed	40	15	4	40	54	HF	2	Eroded (500)				155 (655)	1.18	131 (555)	0.13 (0.555)	**Lower bank:**	**655**	**0.13 (0.655)**
Upper Chertsey		**8-Jul-92**	**23-Aug-92**	**27-Sep-92**	**29-Oct-92**	**11-Jan-92**	**9-May-93**													
Profile 1	Upper pin	Installed	9	8	60	30	15							122	0.83	146.988	0.147	**Upper bank:**	**313**	**0.094**
Profile 1	Lower pin	Installed	14	HF	25	HF	25							64	0.83	77.108	0.077	**Lower bank:**	**183**	**0.055**
Profile 2	Upper pin	Installed	43	54	0	0	0							97	0.83	116.867	0.117			
Profile 2	Lower pin	Installed	2	HF	15	HF	2							19	0.83	22.892	0.023			
Profile 3	Upper pin	Installed	15	16	10	2	M							43	0.83	51.807	0.052			
Profile 3	Lower pin	Installed	3	67	30	HF	M							100	0.83	120.482	0.120			
Profile 4	Upper pin	Installed	7	3	0	HF	41							51	0.83	61.446	0.061			
Profile 4	Lower pin	Installed	0	HF	0	HF	M							0	0.83	0	0			
Lower Chertsey		**6-Mar-92**	**13-Apr-92**	**10-May-92**	**14-Jun-92**	**20-Jul-92**	**23-Aug-92**	**27-Sep-92**	**29-Oct-92**	**11-Jan-93**	**9-May-93**									
Profile 3	Upper pin	Installed	12	0	20	0	10	0	0	3	35			80	1.18	67.797	0.068	**Upper bank:**	**332**	**0.094**
Profile 3	Lower pin	Installed	9	0	0	0	0	HF	0	HF	M			9	1.18	7.627	0.008	**Lower bank:**	**108**	**0.031**
Profile 4	Upper pin	Installed	15	7	0	0	0	0	20	48	28			118	1.18	100.000	0.100			
Profile 4	Lower pin	Installed	34	5	0	0	0	HF	15	HF	45			99	1.18	83.898	0.084			
Profile 5	Upper pin	Installed	0	6	0	0	0	25	0	46	57			134	1.18	113.559	0.114			
Profile 5	Lower pin	Installed	0	0	0	0	0	HF	0	HF	M			0	1.18	0	0			

Note: Values of erosion shown in brackets include estimates of erosion

Installed = date erosion pin was installed

RP = re-pinned

HF = high flow prevented measurement of erosion

Vegetation = growth of vegetation prevented measurement of erosion

Deposition = deposition over the erosin pin prevented measurement of erosion

Eroded = where pin was eroded

M = missing erosion pin

Legend:

- (salmon) denotes where erosion is attributed to frost and needle ice
- (red diagonal strokes) denotes where erosion is attributed to cattle 'poaching'
- (white) denotes where erosion is attributed to wetting and drying cycles
- (blue) denotes where erosion is attributed to the high flows in April 1992
- (yellow) denotes where erosion is attributed to the high flows in September 1992
- (red) denotes where erosion is attributed to the high flows in Winter 1992-93
- (green) denotes where erosion is attributed to the high flows in April 1993 (and a combination of other factors)
- (pink) denotes where erosion is attributed to a combination of high flows in Winter 1992-93 and April 1993

Although erosion mechanisms are impossible to isolate completely, contributory factors include cattle trampling, which results in mechanical damage to the bank, boat wash and the high flow velocities experienced in the autumn and winter. During the winter months, boat traffic is at a minimum and the banks were no longer grazed by cattle. However, the protective reeds and bank vegetation died back, leaving the bank more exposed to the erosive force of the high winter discharges.

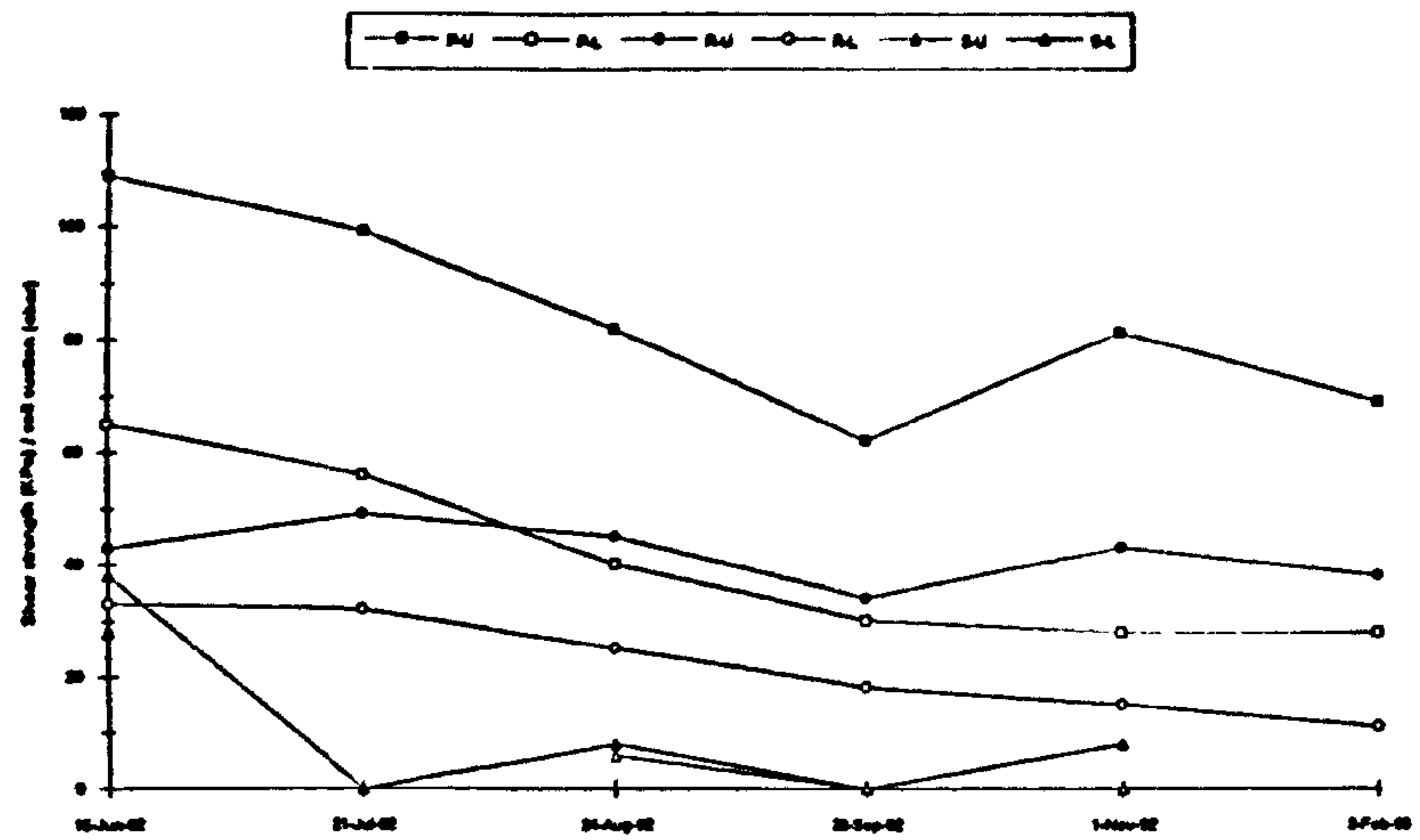
Limited upper bank erosion was measured during the first two months of the monitoring period (10 March to 10 May 1992), when there was 9mm of erosion, compared to 31mm at the lower bank. Disregarding the August result, when the upper and lower banks were repinned, the only other erosion of the upper bank took place between 29 September and 1 November 1992, when 15mm of erosion was recorded. From the seasonal pattern of upper and lower bank erosion, the high autumn flows appear to have made a considerable contribution to erosion. However, without the erosion pin exposure data for August 1992, the contribution to erosion during the summer is unknown.

The bank surveys taken at profile two indicate that there was approximately 300mm of erosion at the lower bank between 6 July and 1 November 1992. There must therefore, have been approximately 150mm of lower bank erosion between 21 July and 24 August 1992. The surveys also shows far less upper bank erosion over this time, no more than about 100mm, so that there was approximately 85mm of erosion at the upper bank between 21 July and 24 August 1992. The bank surveys at profiles three, four and five show varying degrees of upper and lower bank distortion. These changes in the bank can be attributed to cattle trampling and changes in bank vegetation and reed growth, all of which had a significant influence on the bank morphology.

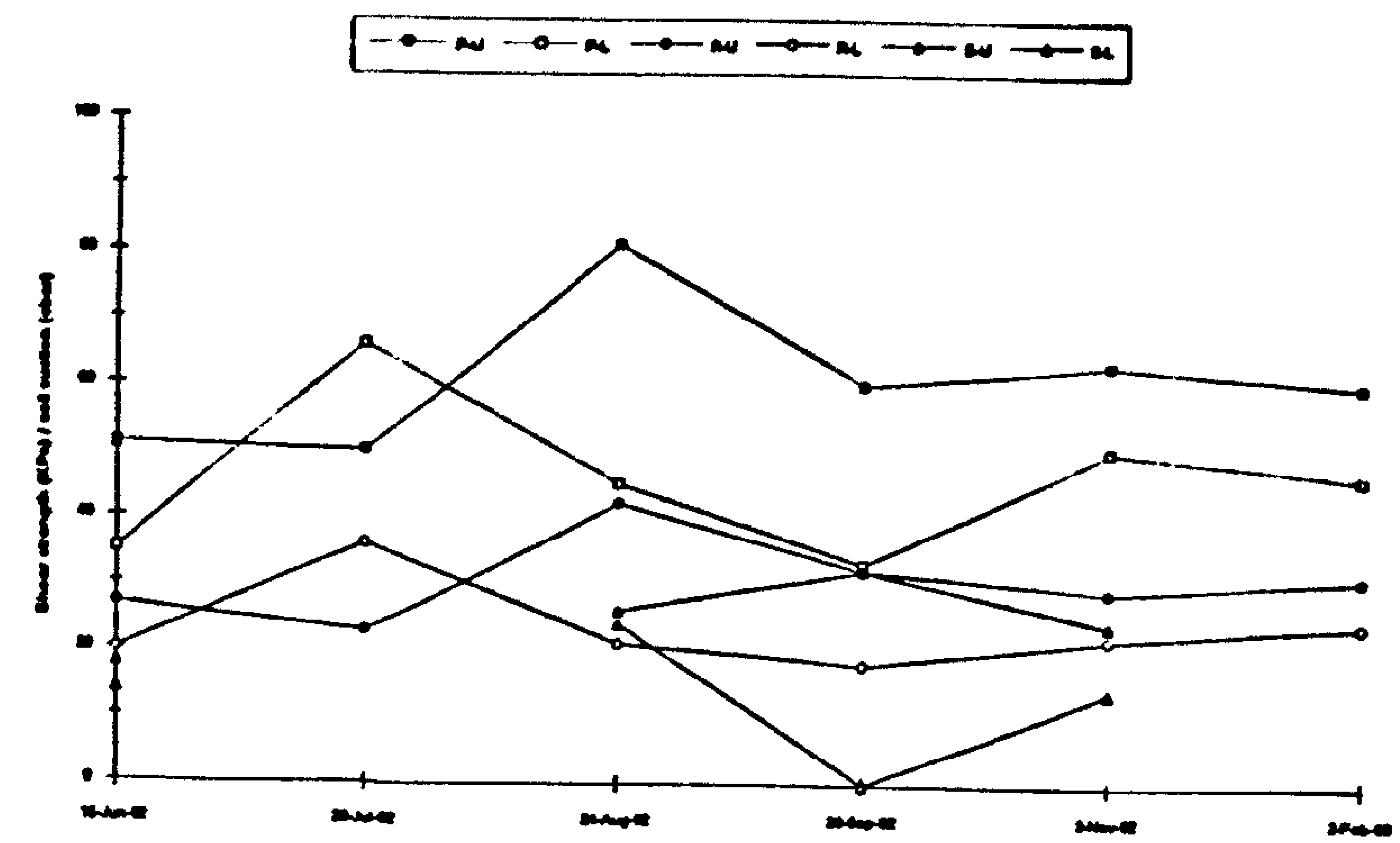
Erosion at the upper and lower bank of profile two was least during the spring, from 10 March to 10 May 1992, and greatest during the summer, from 10 May 1992 to 24 August 1992. The summer period corresponds to the peak boating

Appendix 4.3 Soil suction and shear strength measurements

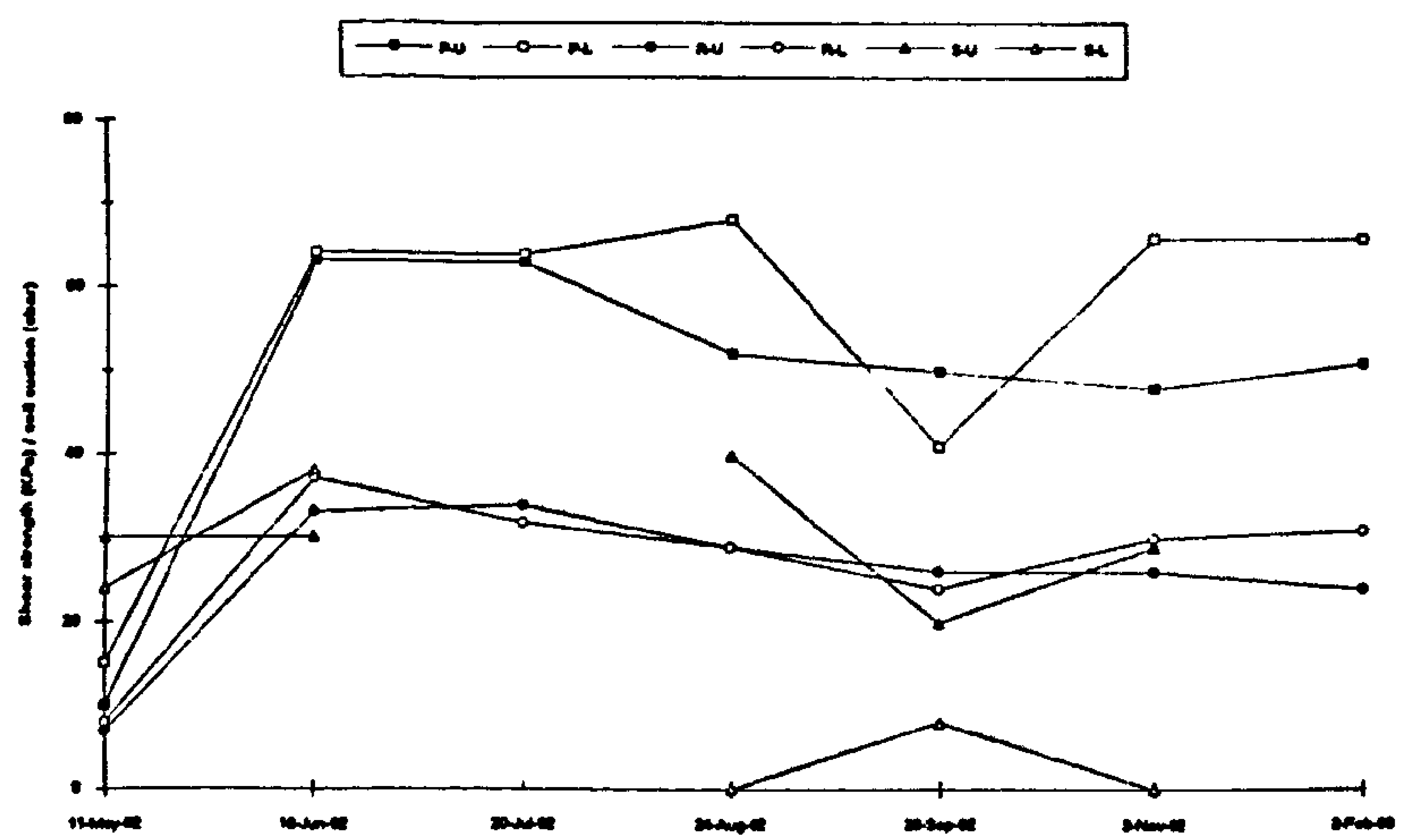
P = peak shear strength R = residual shear strength S = soil suction
U = upper bank L = lower bank



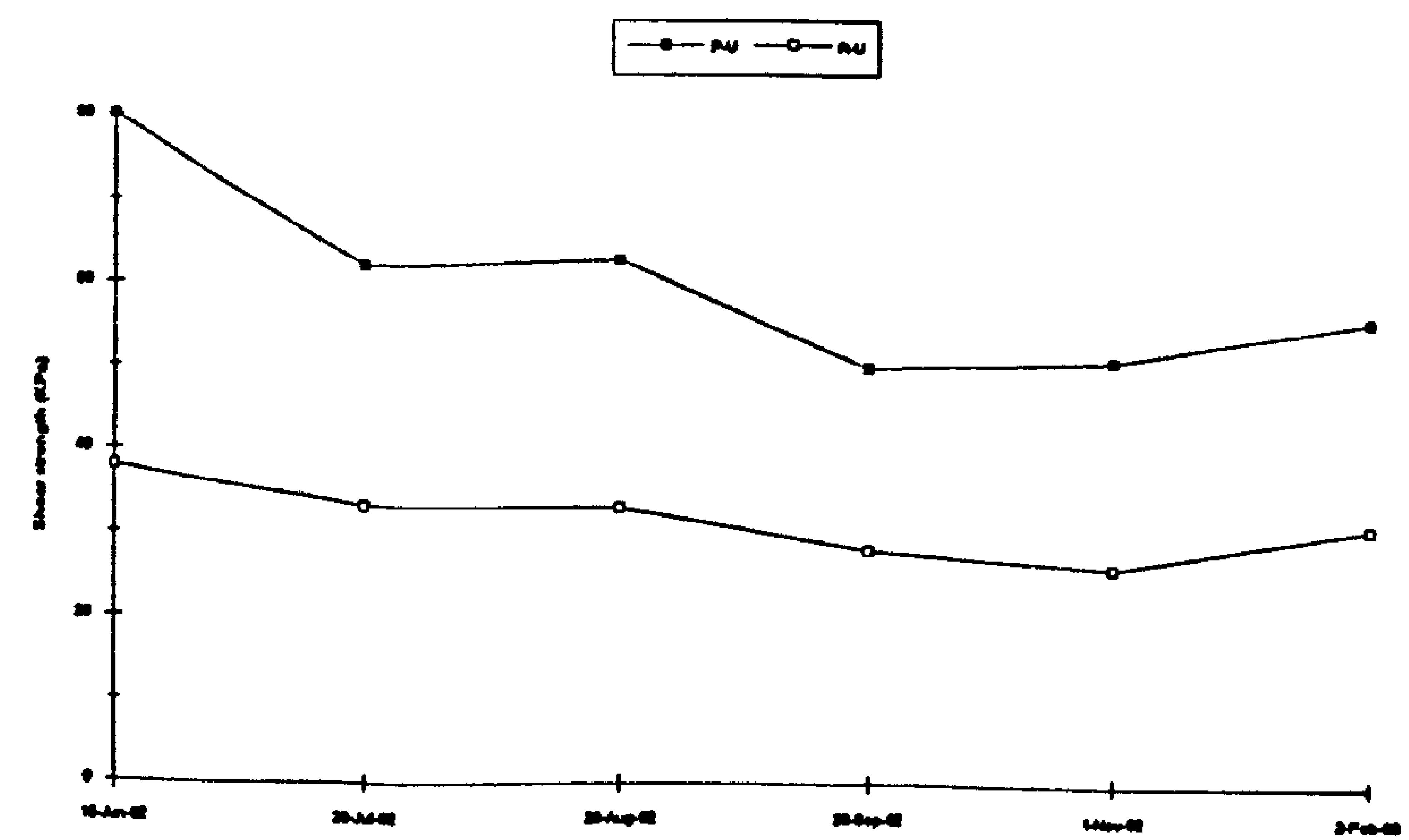
Soil shear strength and suction measured at the St.John's monitoring site



Soil shear strength and suction measured at the Upper Wallingford monitoring site

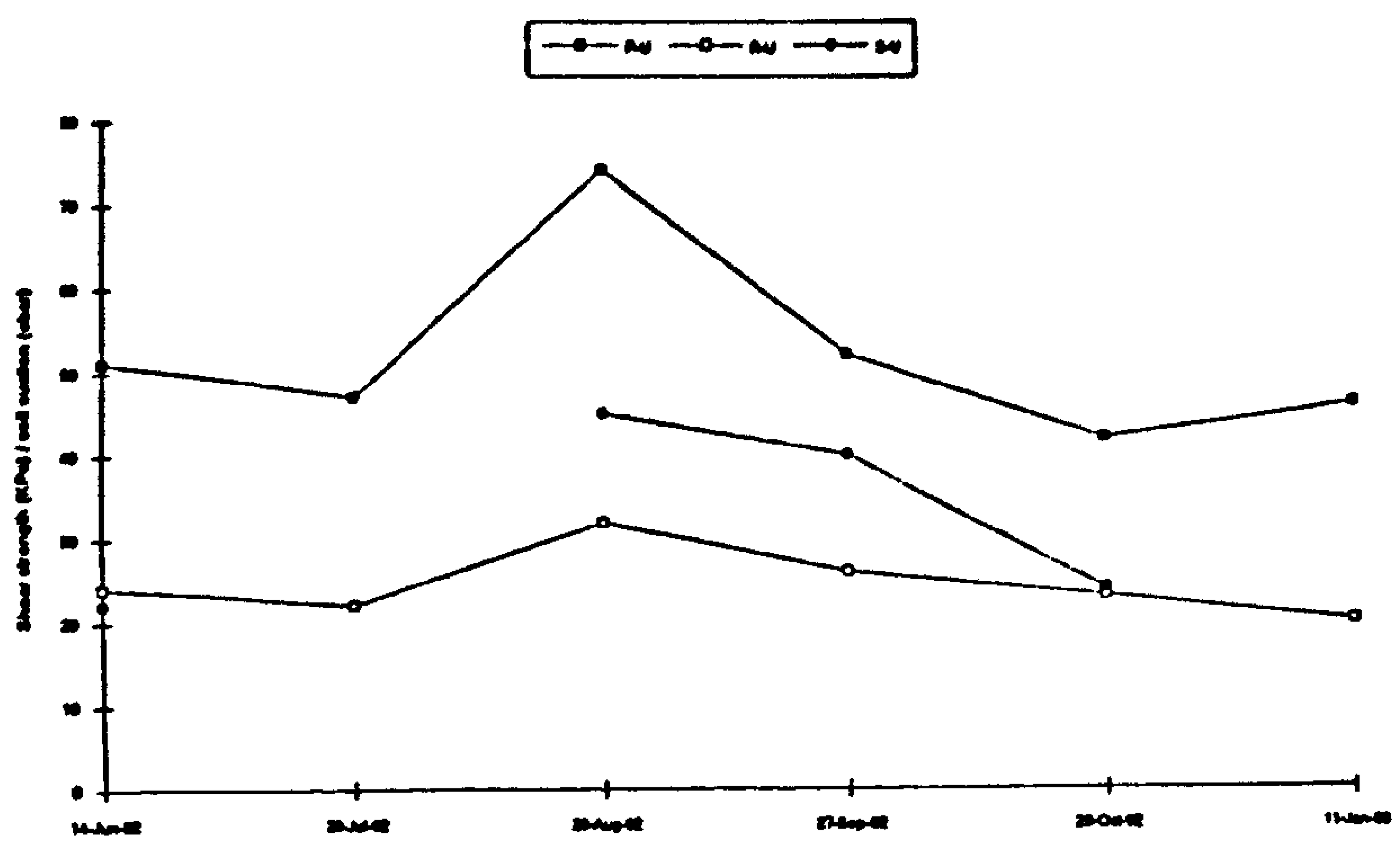


Soil shear strength and suction measured at the Lower Wallingford monitoring site

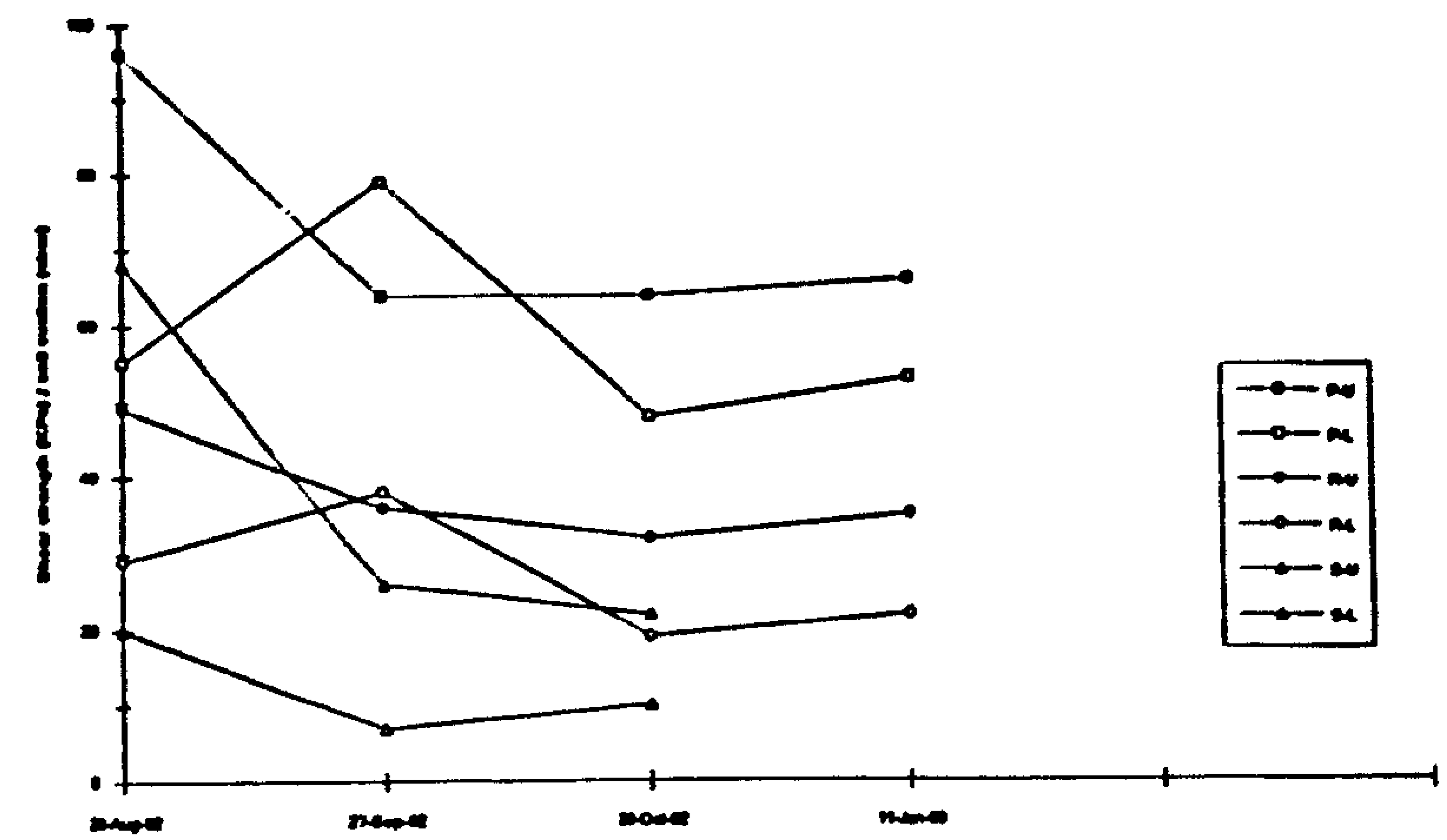


Soil shear strength measured at the Goring monitoring site (suction remained at zero throughout)

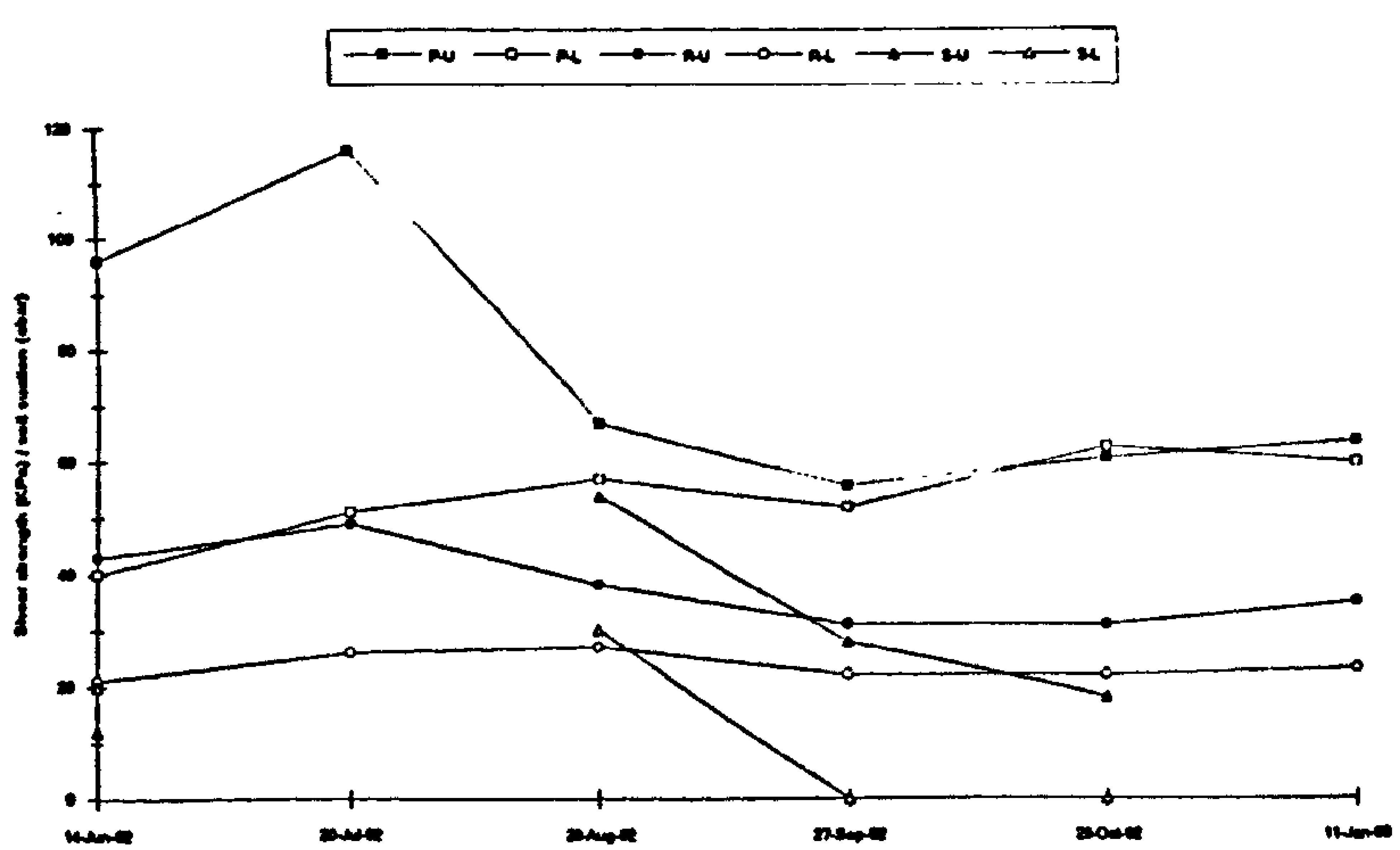
Appendix 4.3 Soil suction and shear strength measurements



Soil shear strength and suction measured at the Laleham monitoring site



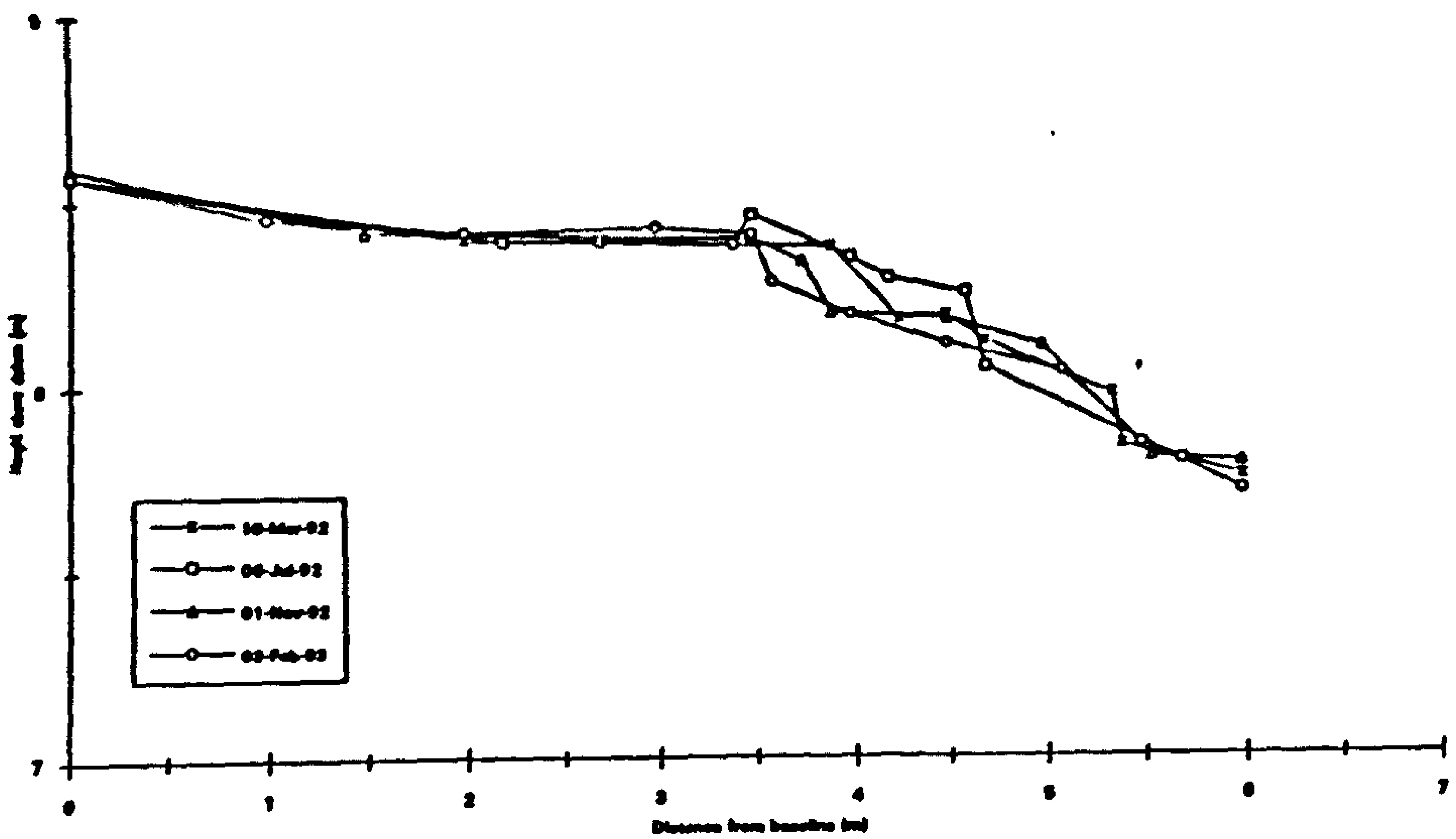
Soil shear strength and suction measured at the Upper Chertsey monitoring site



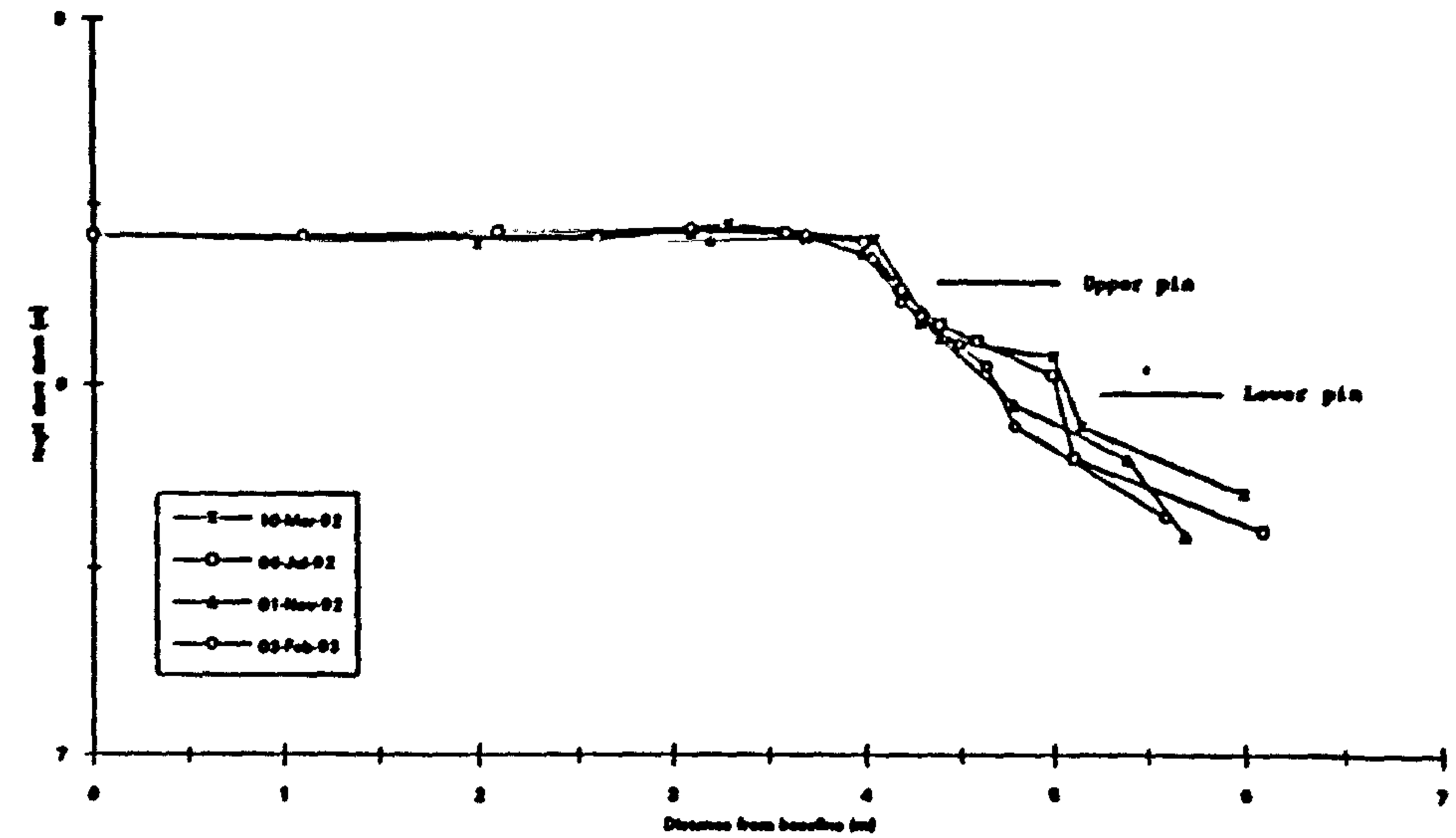
Soil shear strength and suction measured at the Lower Chertsey monitoring site

P = peak shear strength
R = residual shear strength
S = soil suction
U = upper bank
L = lower bank

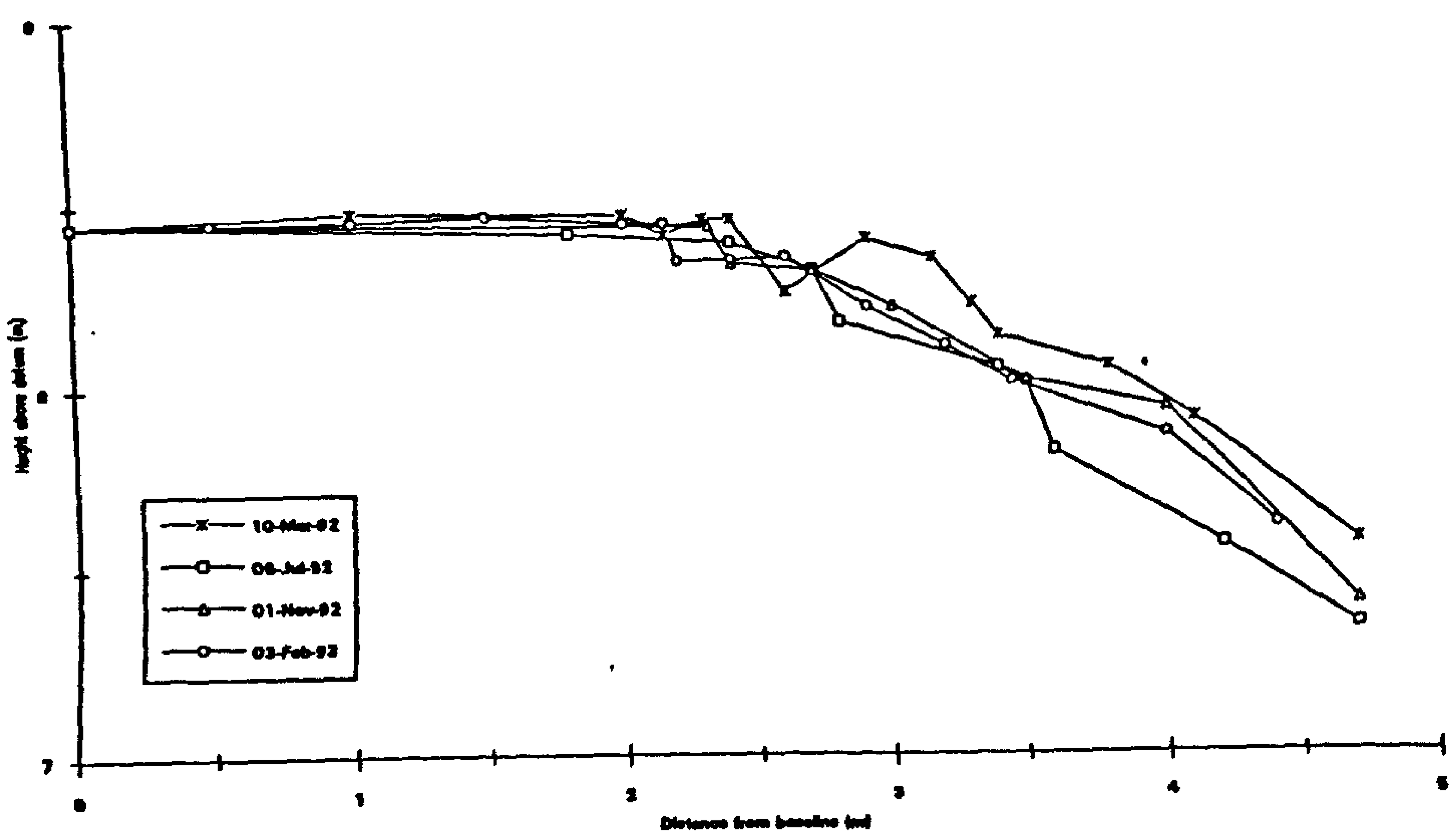
Appendix 4.4 Surveys of bank profiles taken at each monitoring site.



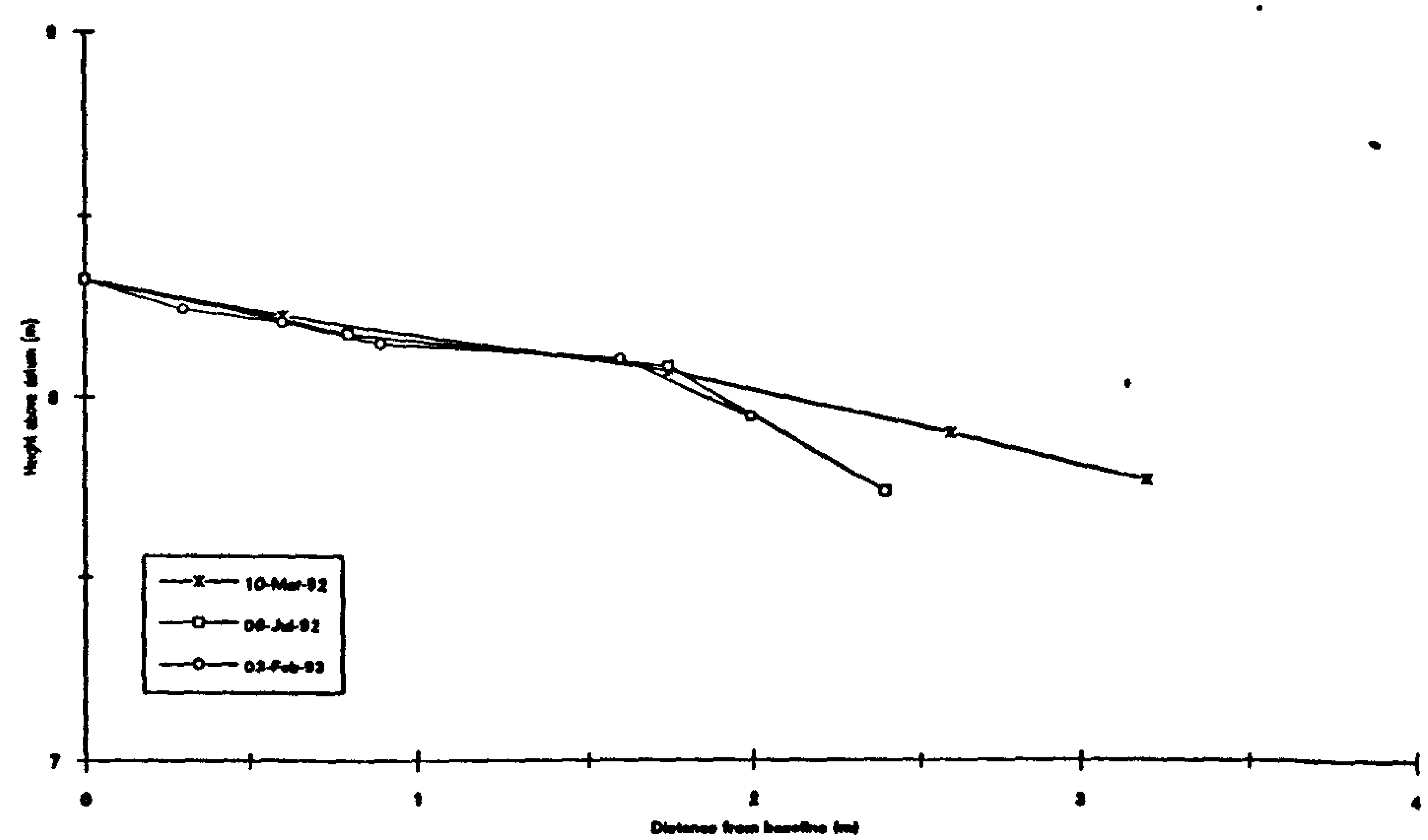
Surveys of the bank at profile one of the St. John's site.



Surveys of the bank at profile two of the St.John's site.



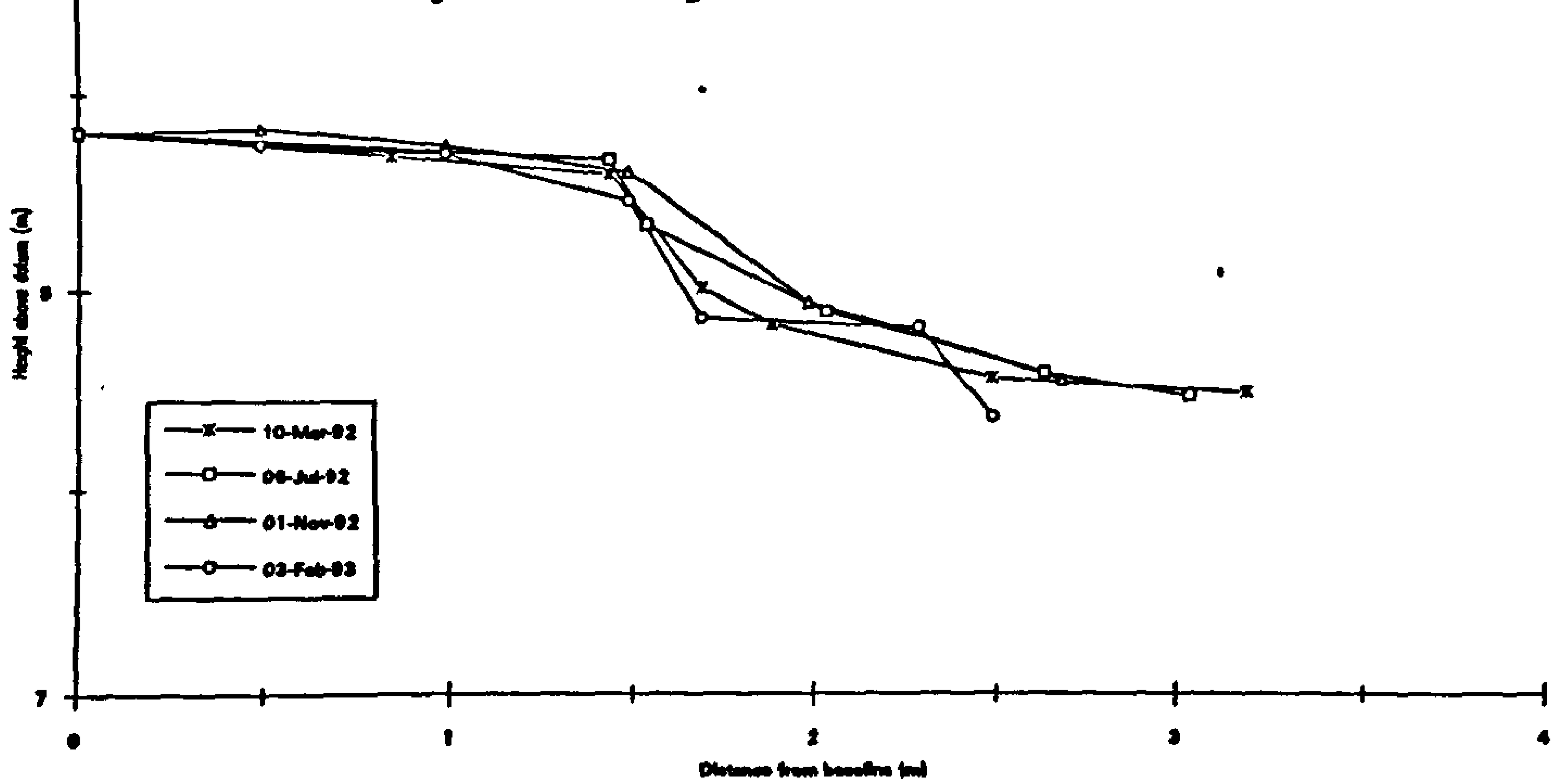
Surveys of the bank at profile three of the St.John's site.



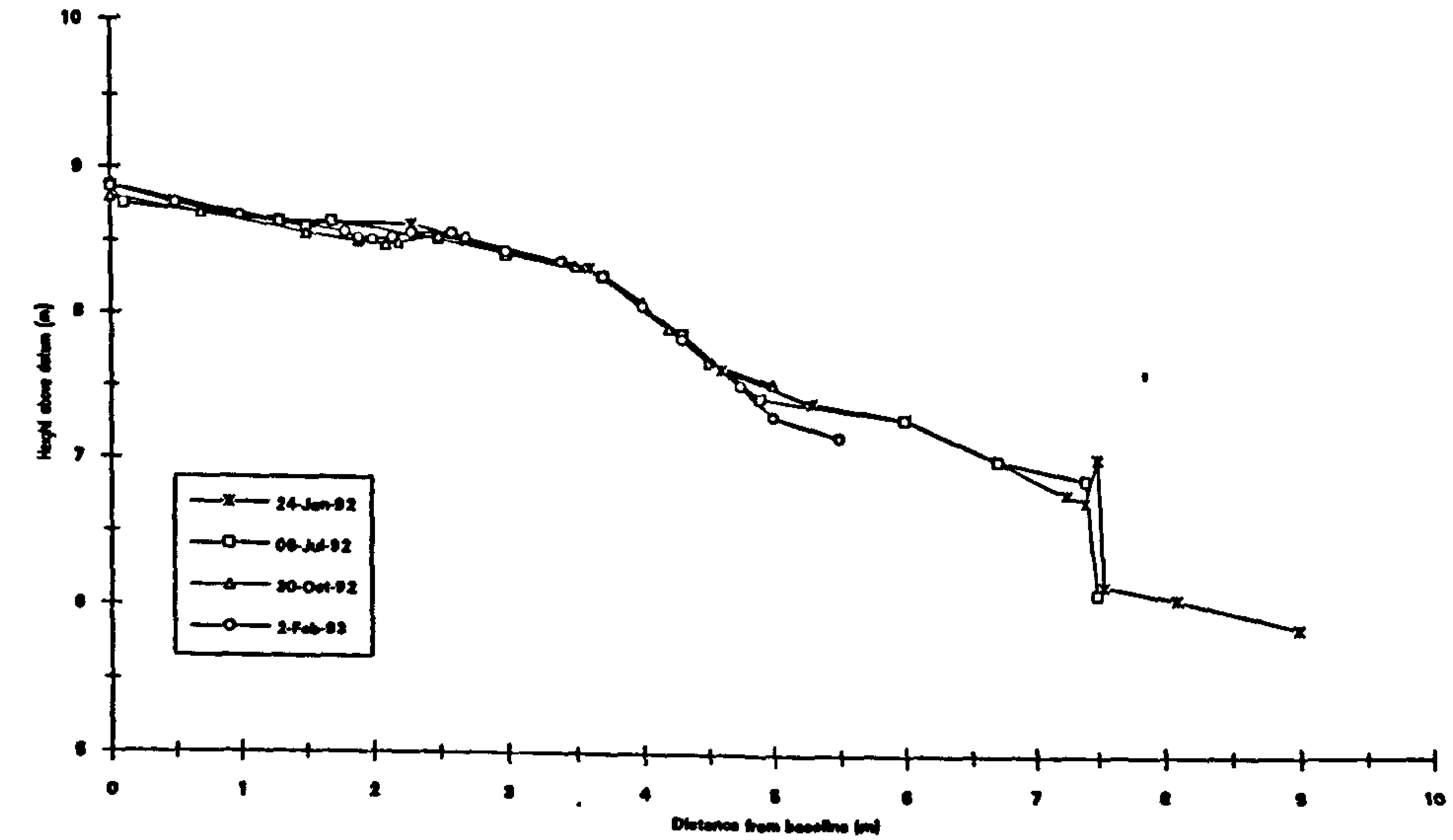
Surveys of the bank at profile four of the St.John's site.

Appendix 4.4 Continued

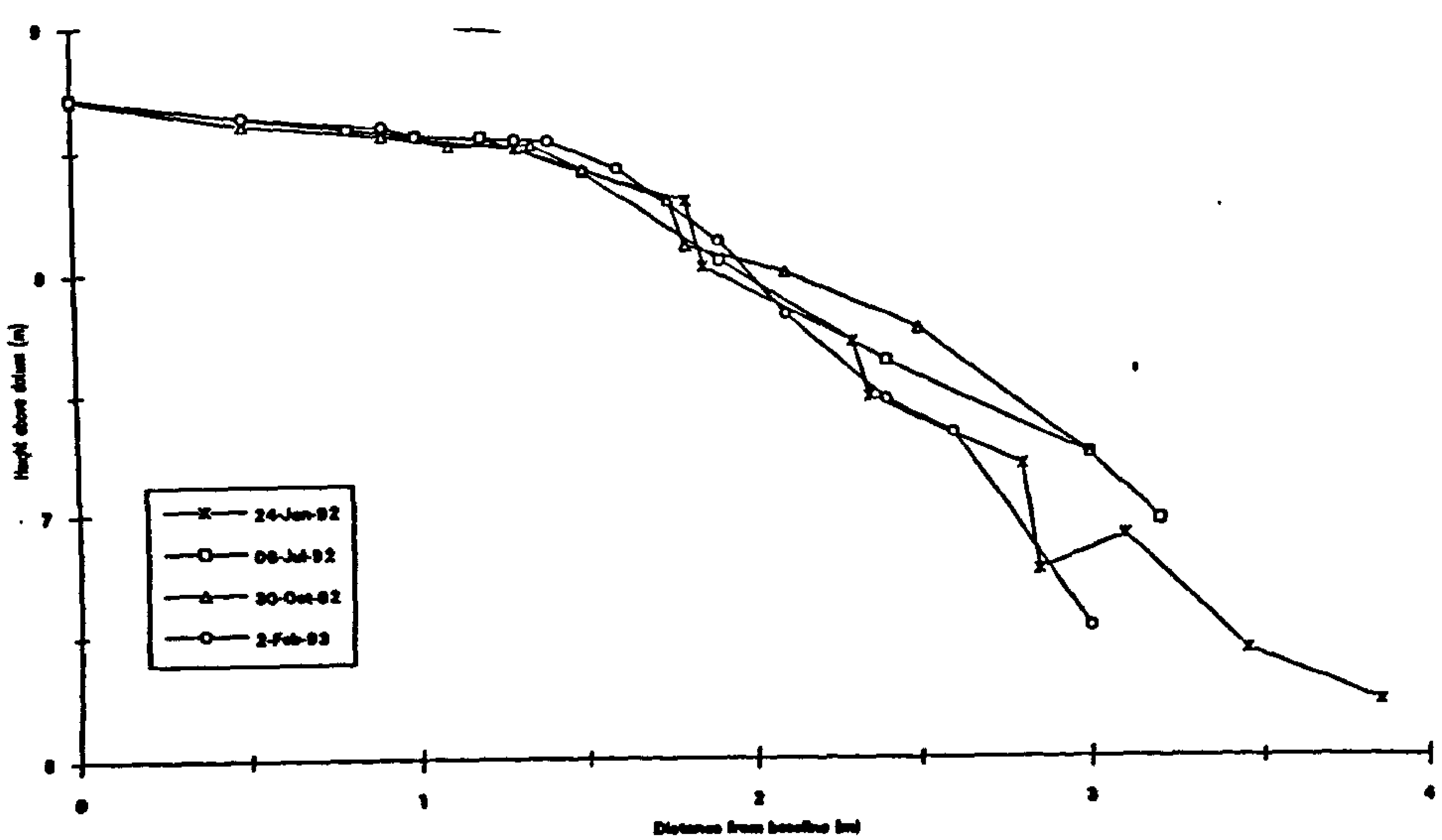
Surveys of bank profiles taken at each monitoring site.



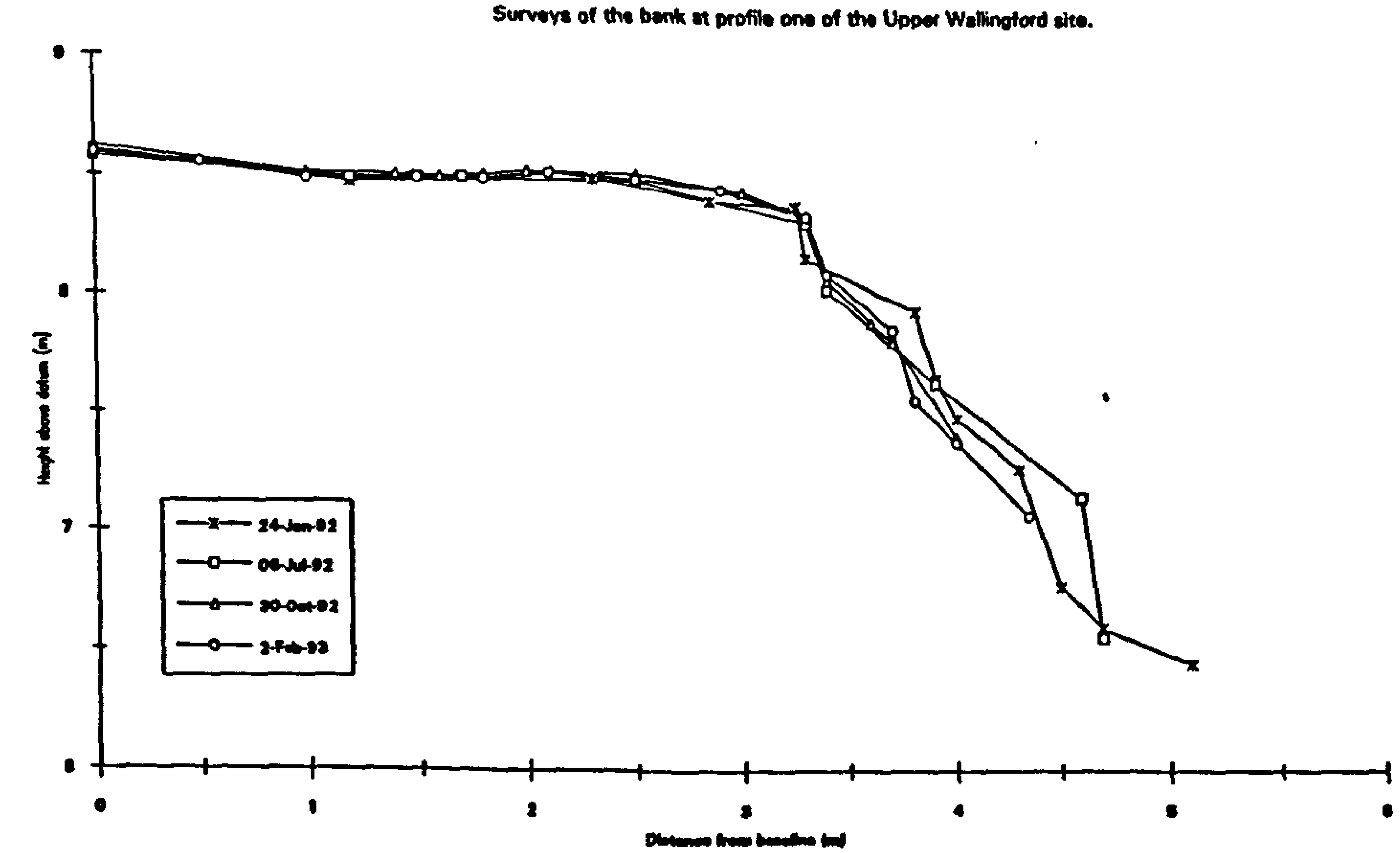
Surveys of the bank at profile five of the St.John's site.



Surveys of the bank at profile one of the Upper Wallingford site.



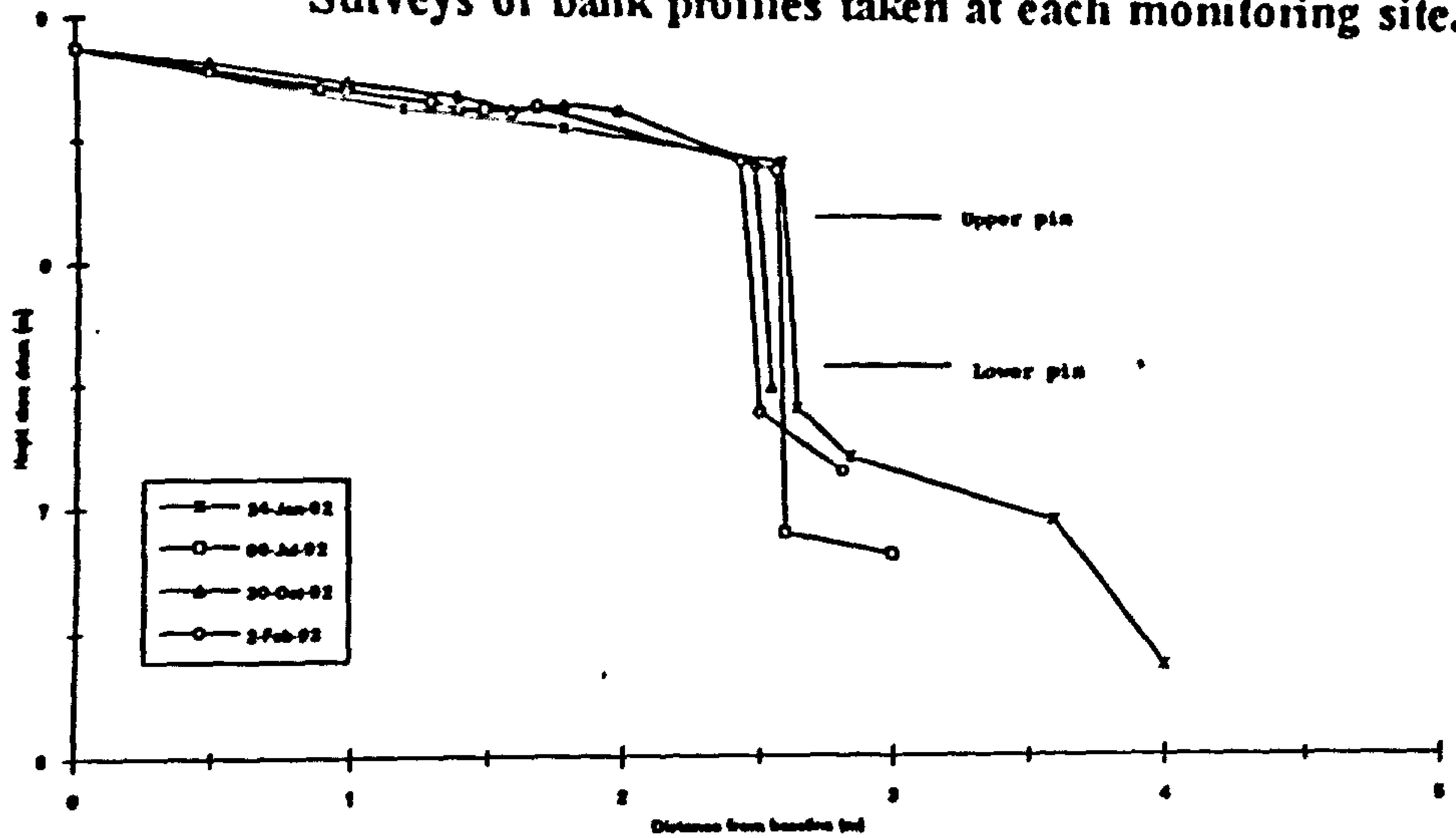
Surveys of the bank at profile two of the Upper Wallingford site.



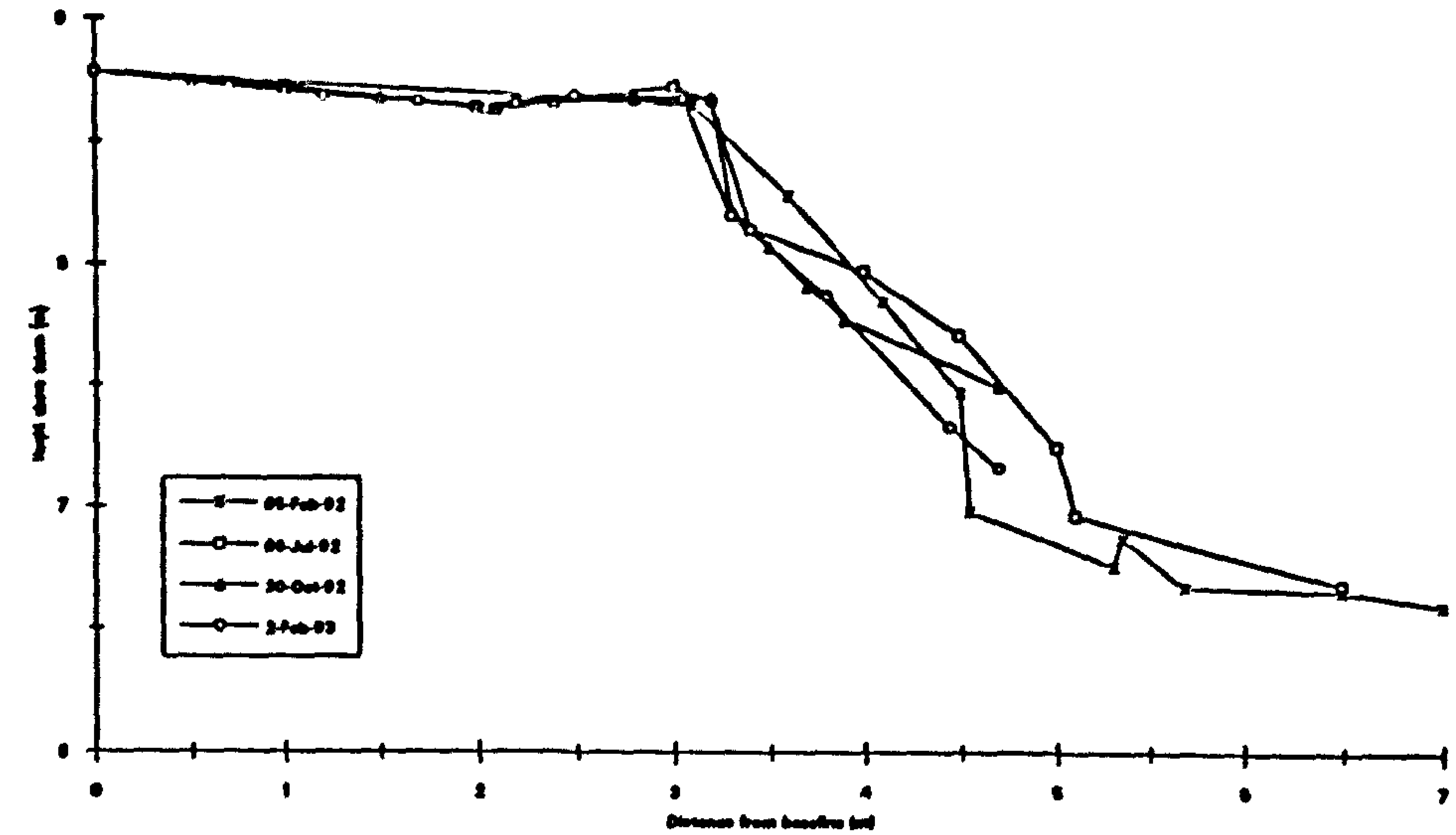
Surveys of the bank at profile three of the Upper Wallingford site.

Appendix 4.4 Continued

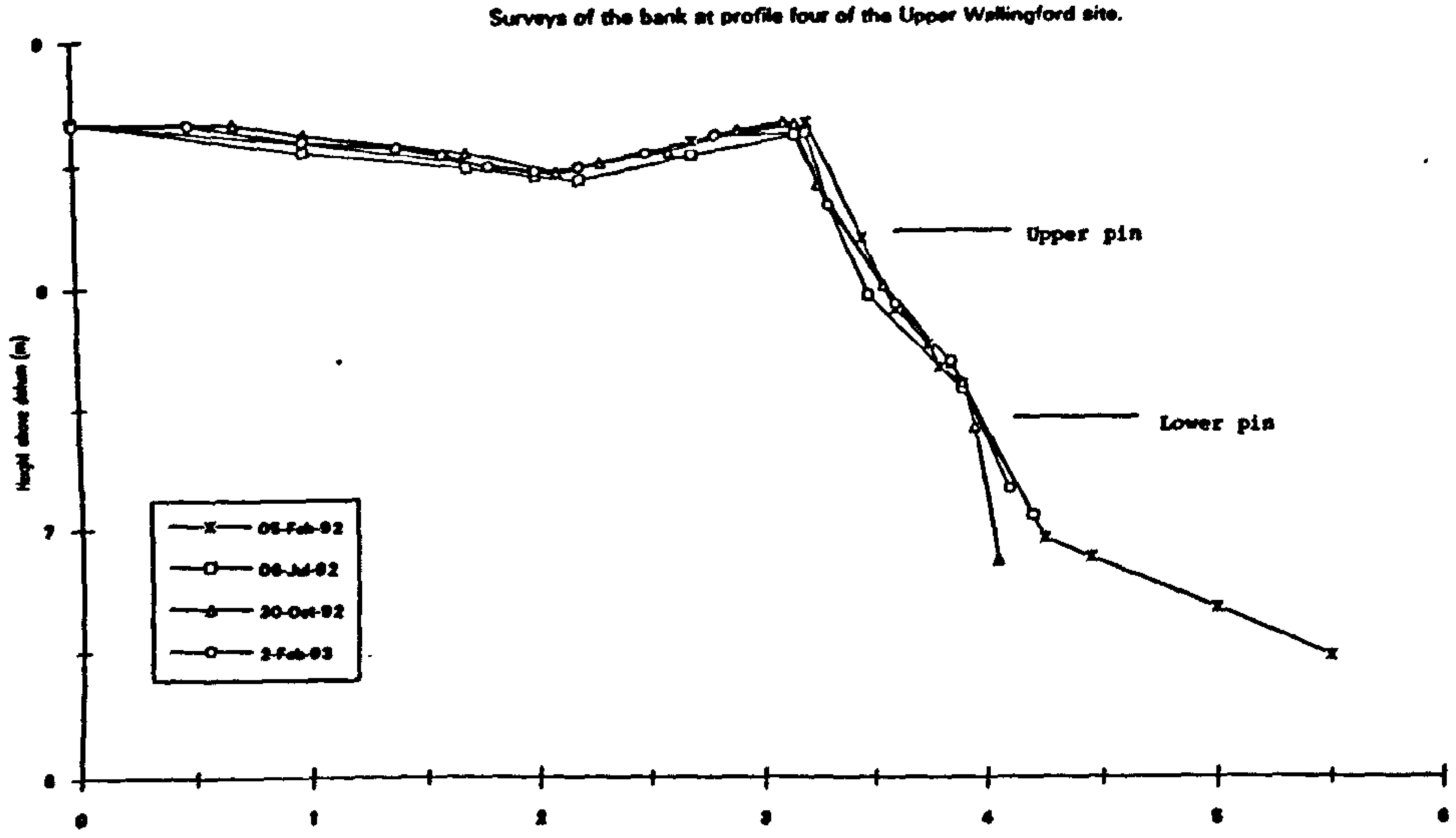
Surveys of bank profiles taken at each monitoring site.



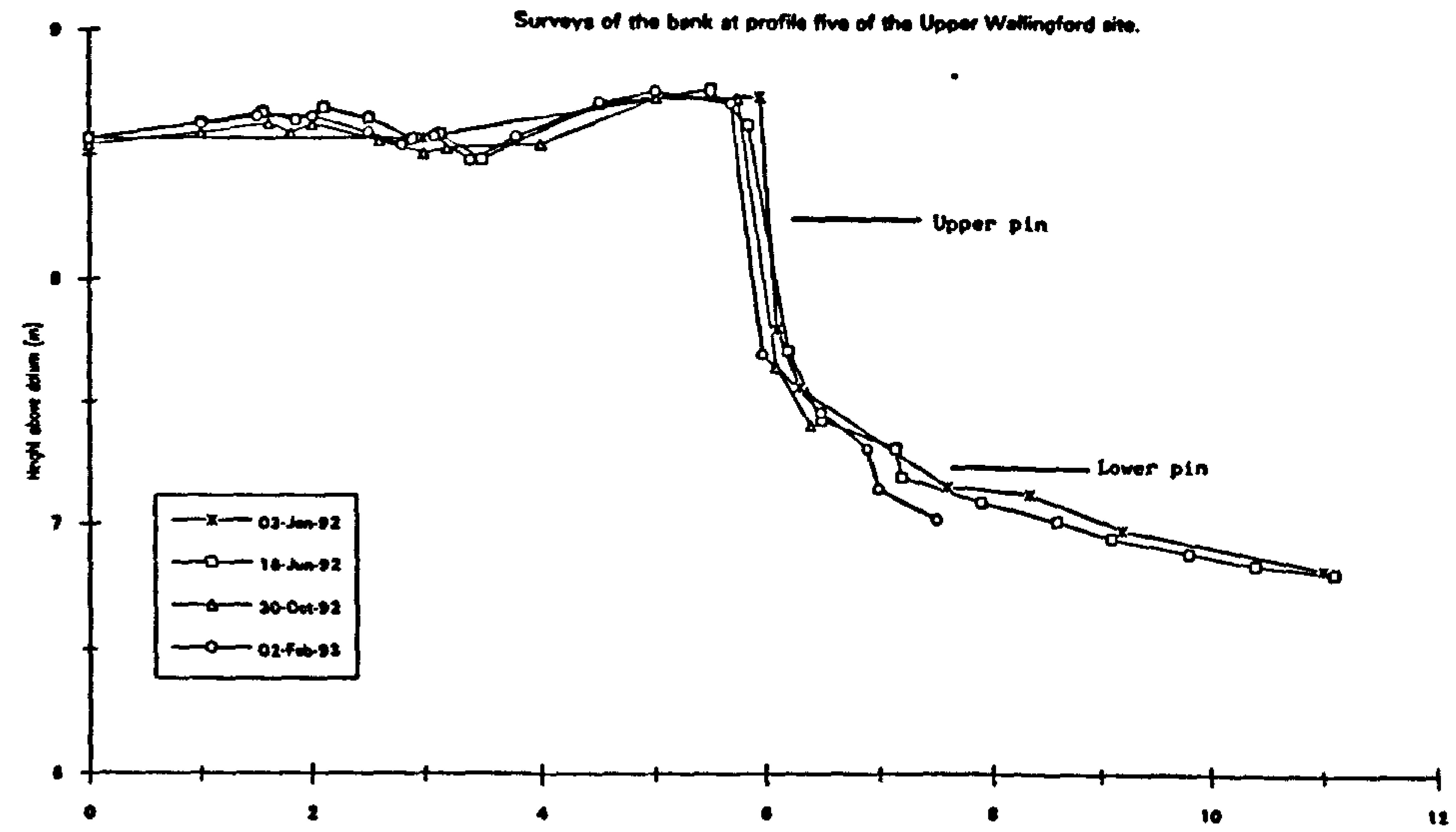
Surveys of the bank at profile four of the Upper Wallingford site.



Surveys of the bank at profile five of the Upper Wallingford site.



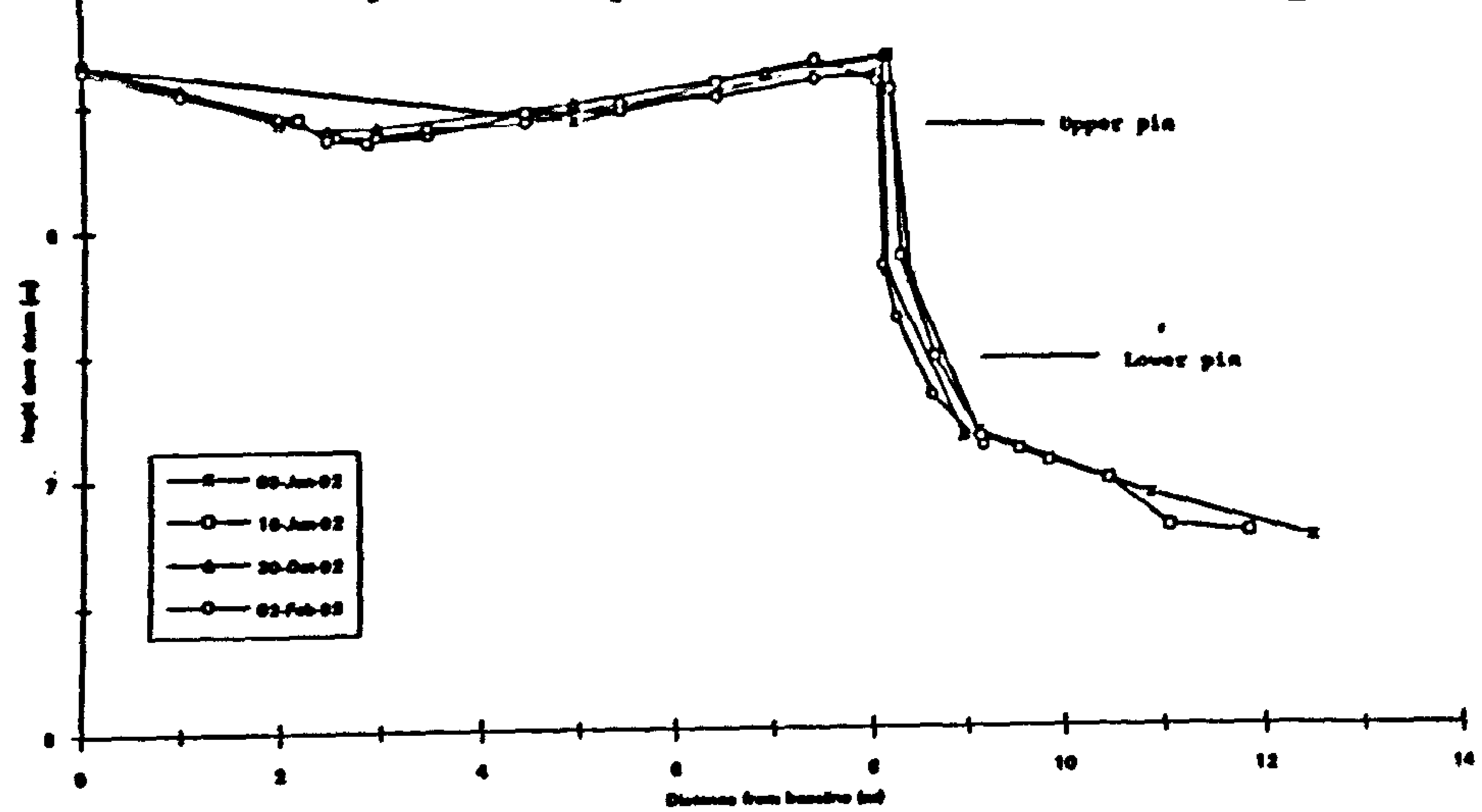
Surveys of the bank at profile six of the Upper Wallingford site.



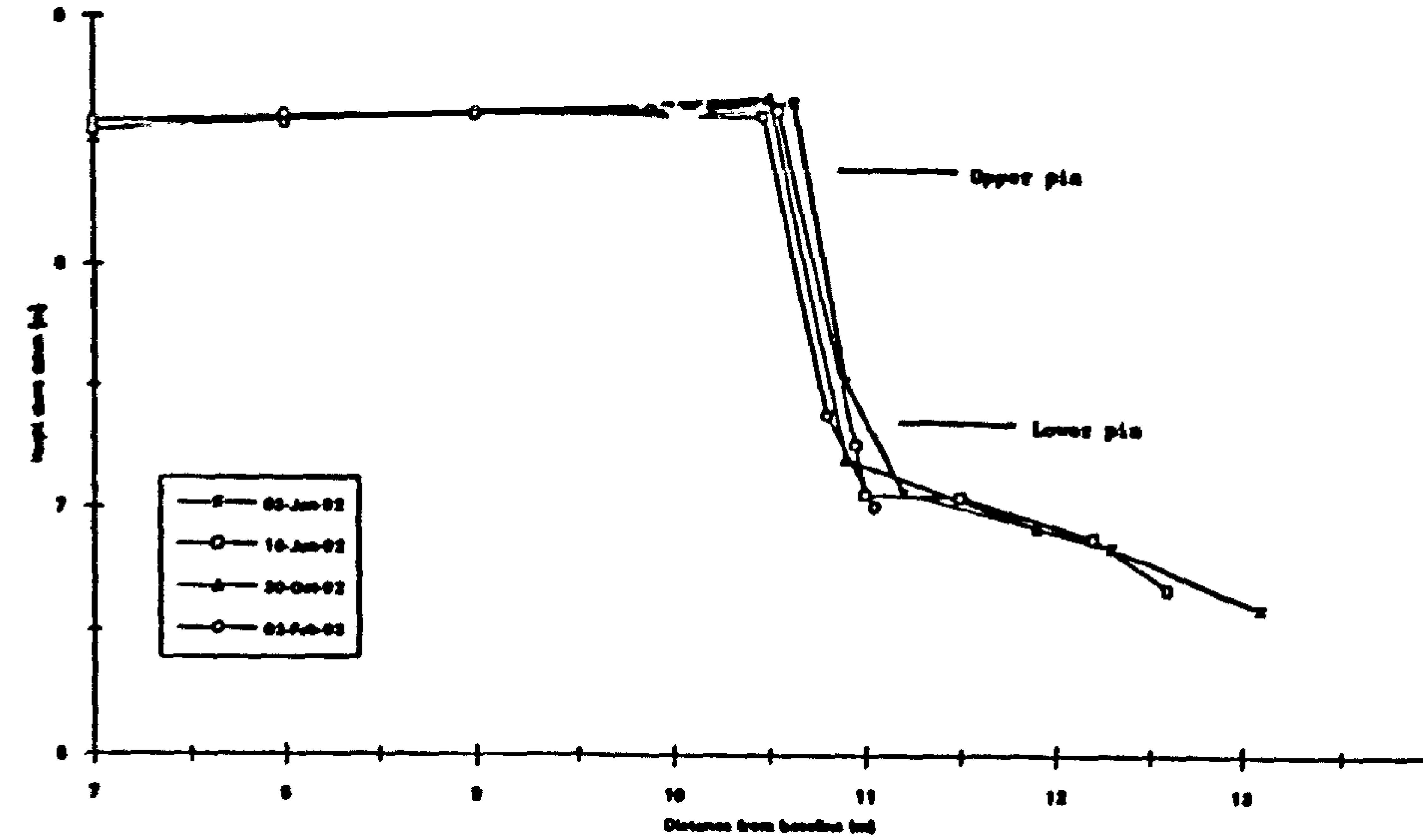
Surveys of the bank at profile one of the Lower Wallingford site.

Appendix 4.4 Continued

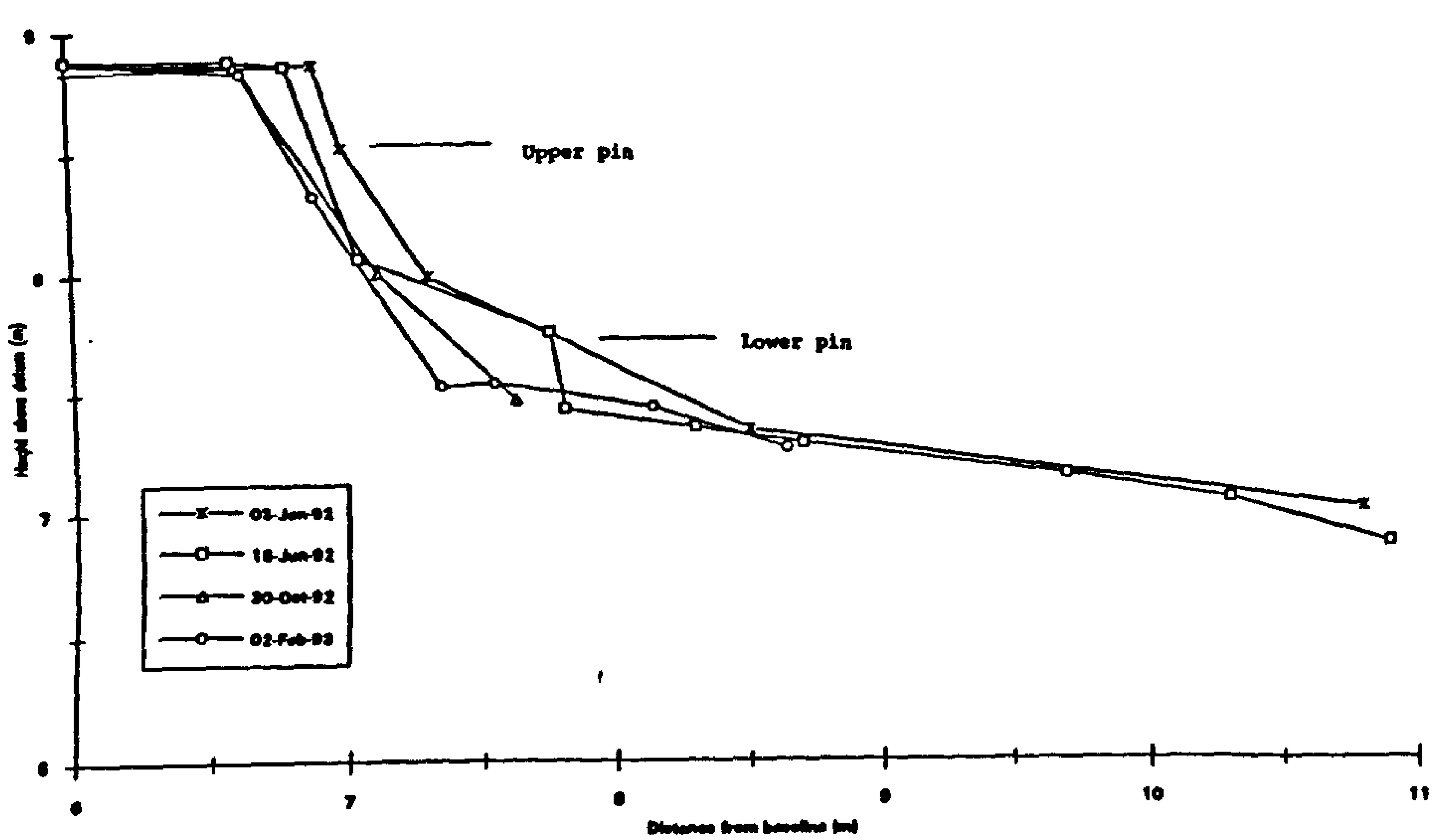
Surveys of bank profiles taken at each monitoring site.



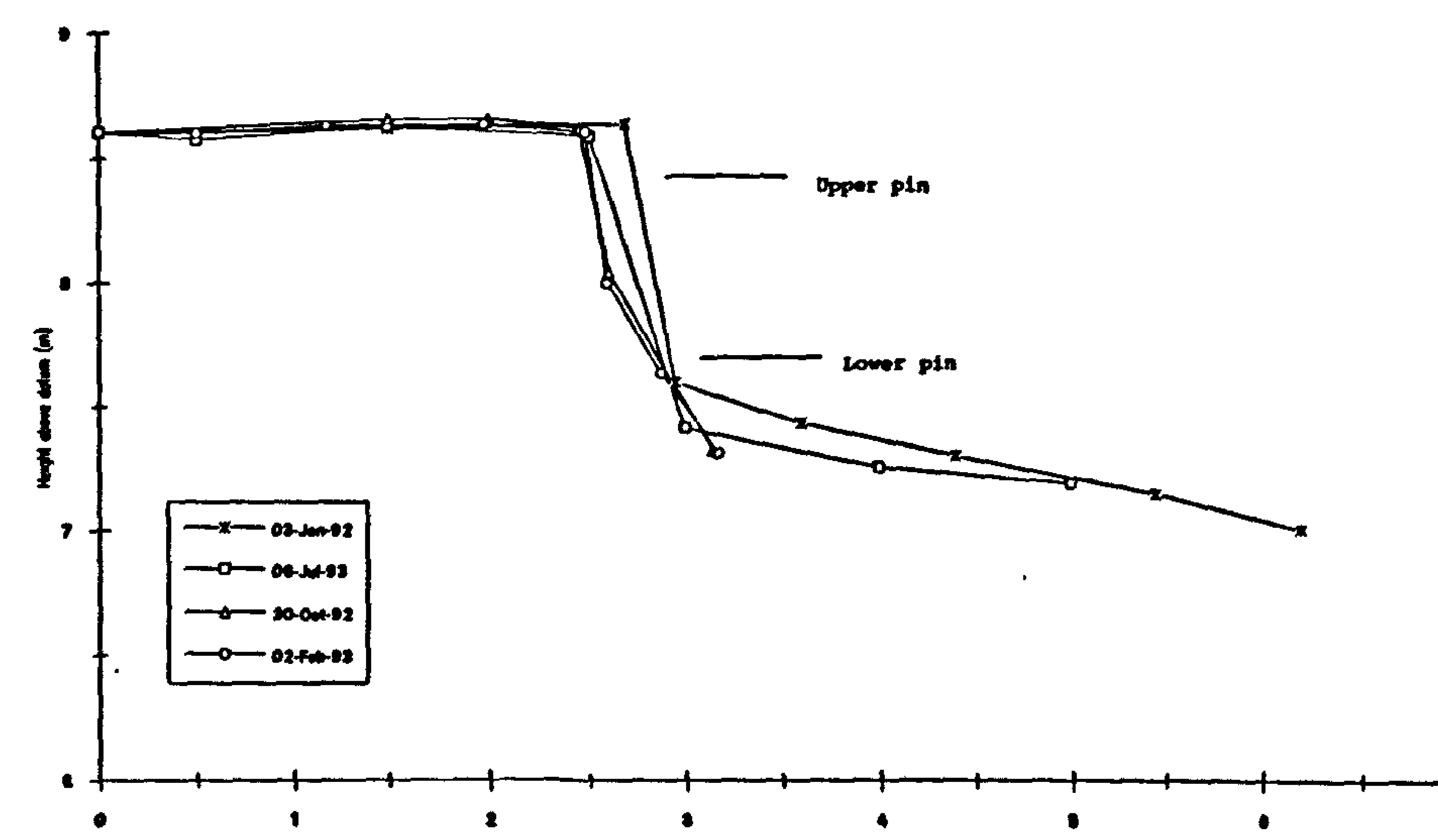
Surveys of the bank at profile two of the Lower Wallingford site.



Surveys of the bank at profile three of the Lower Wallingford site.



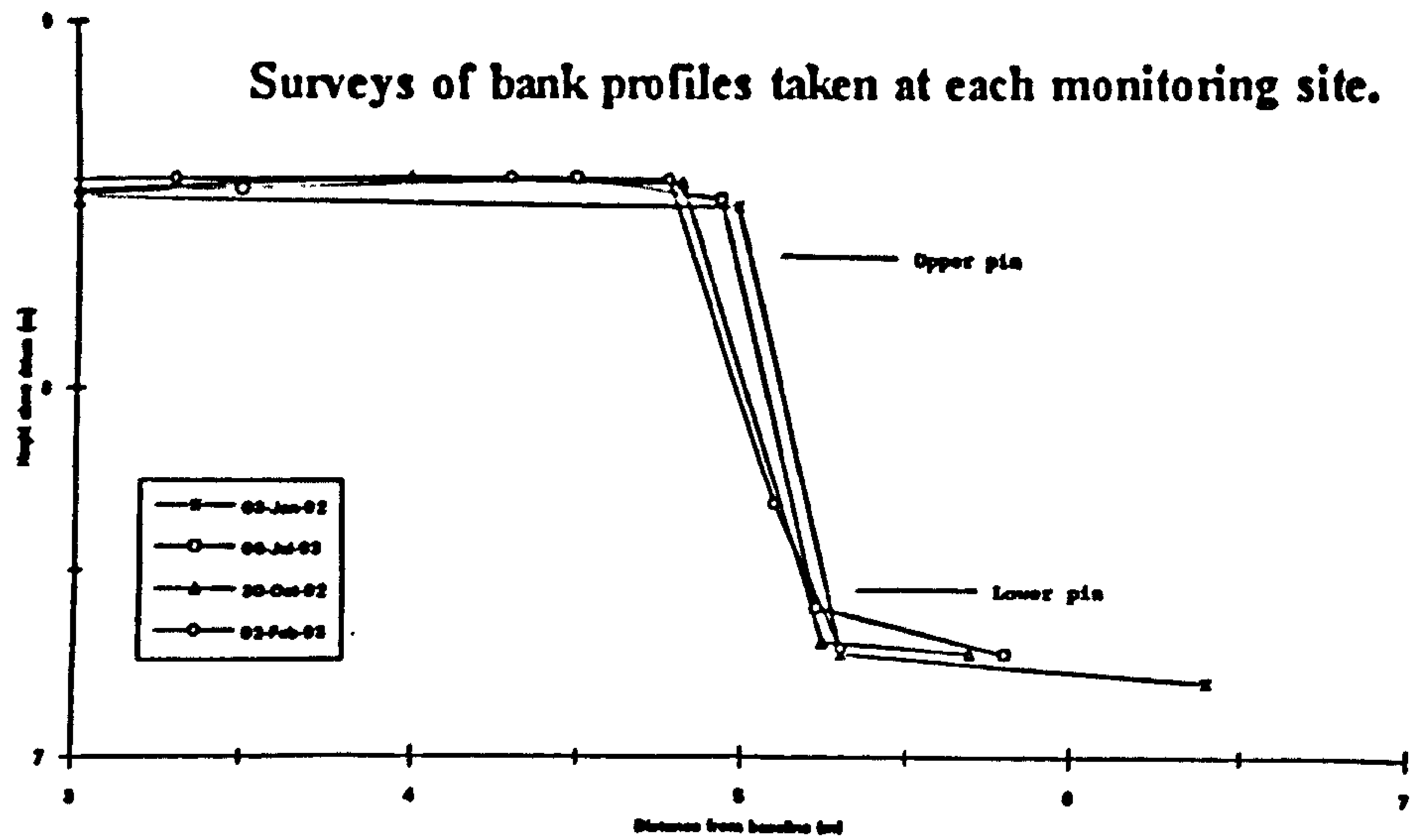
Surveys of the bank at profile four of the Lower Wallingford site.



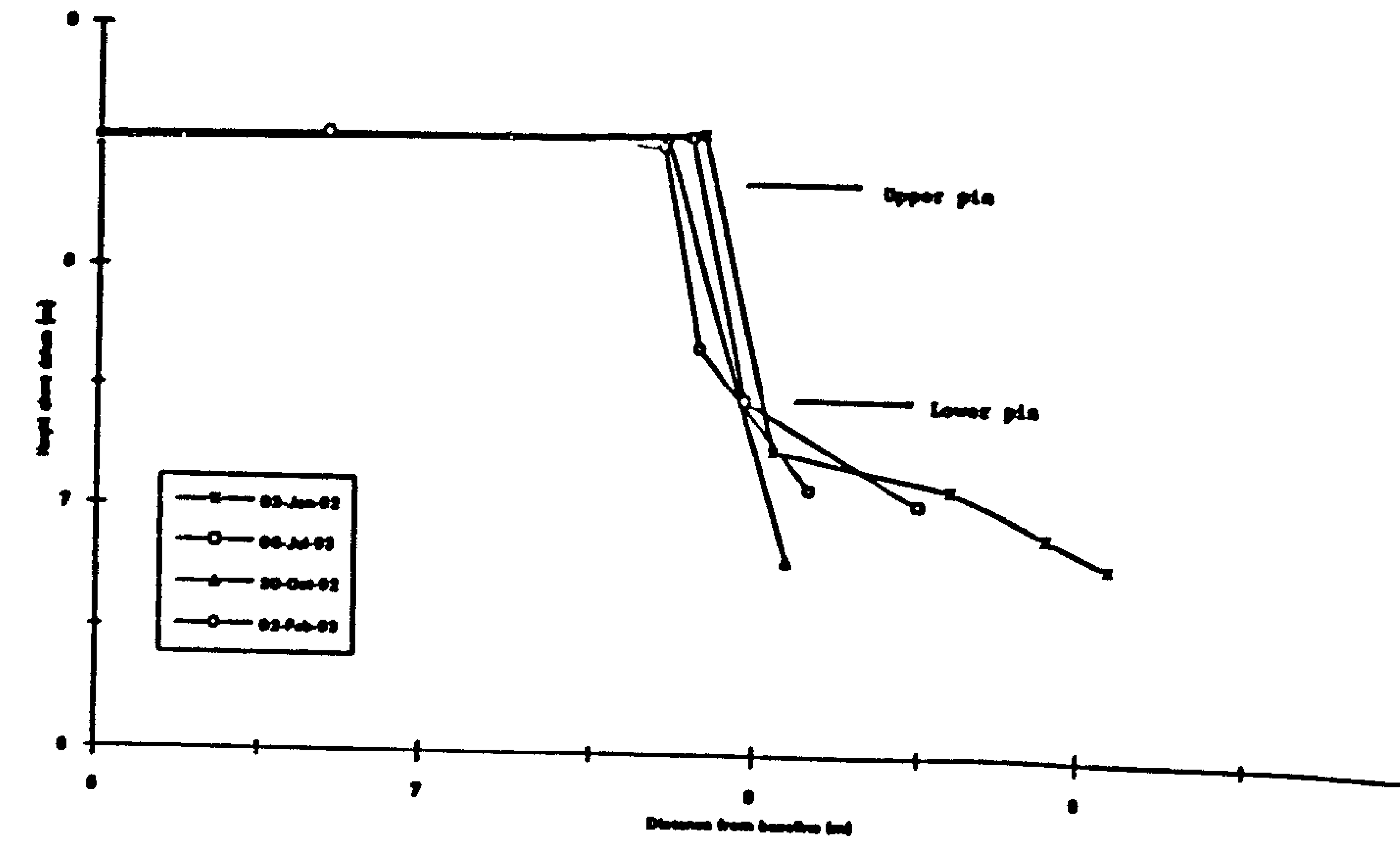
Surveys of the bank at profile five of the Lower Wallingford site.

Appendix 4.4 Continued

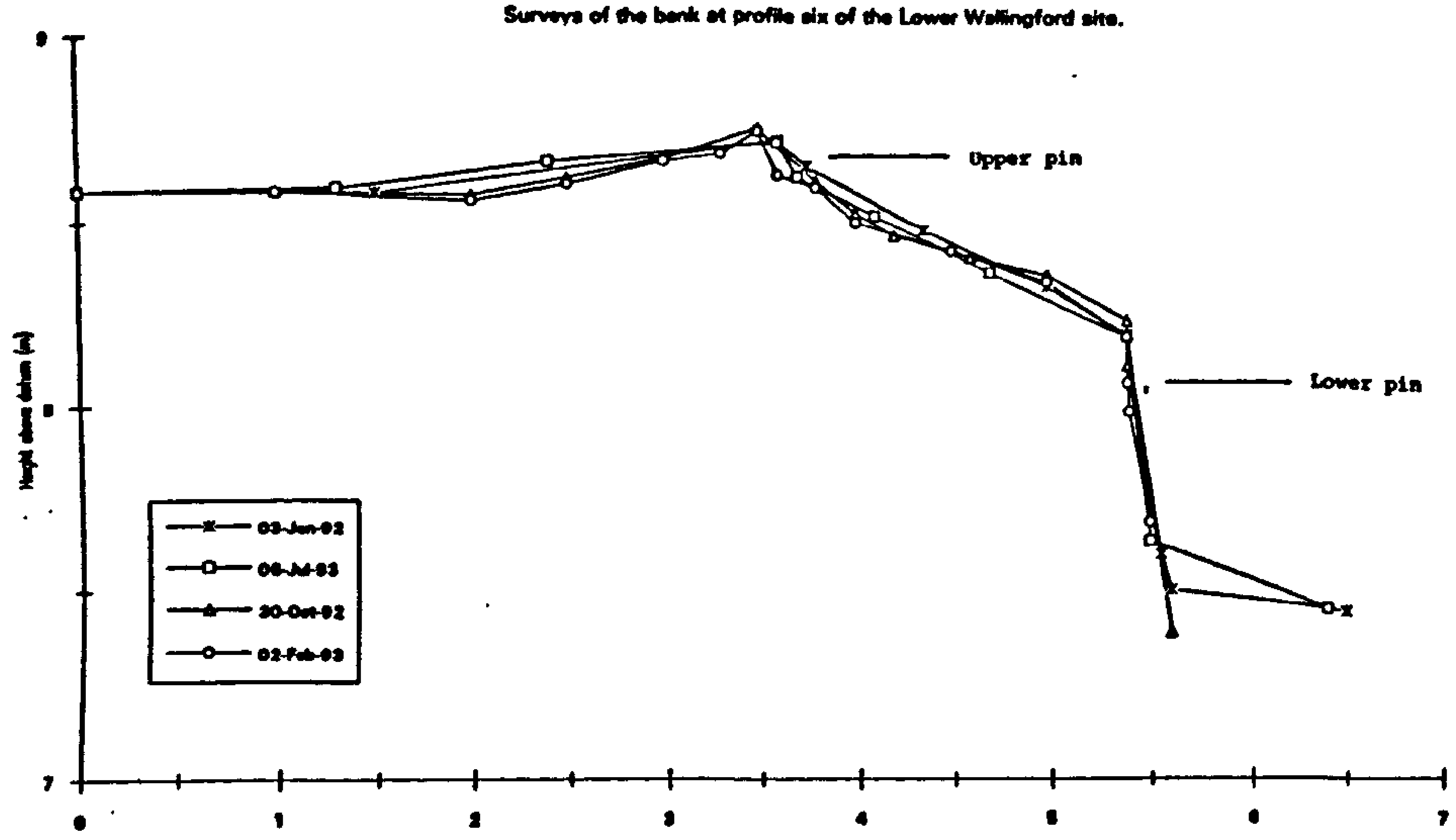
Surveys of bank profiles taken at each monitoring site.



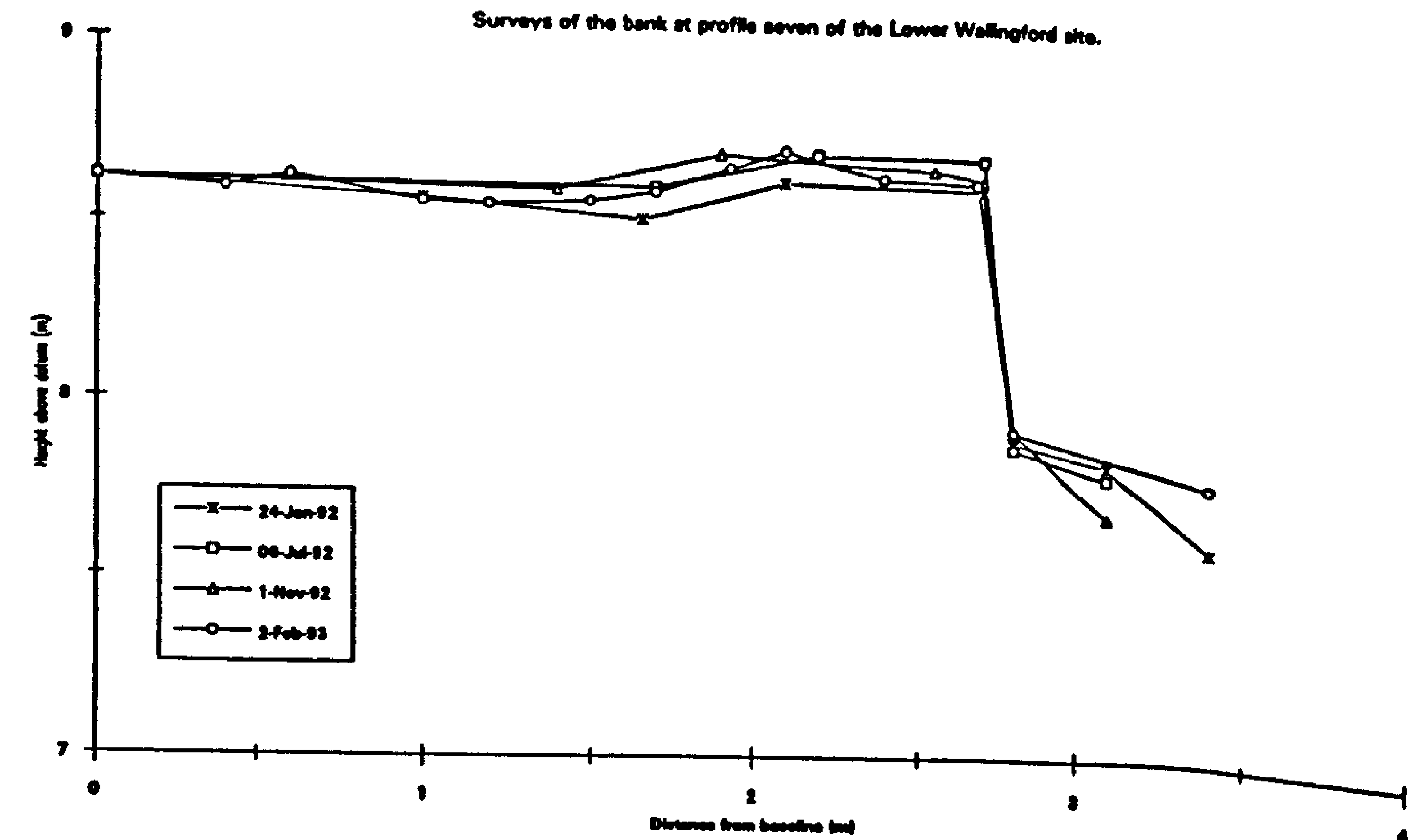
Surveys of the bank at profile six of the Lower Wallingford site.



Surveys of the bank at profile seven of the Lower Wallingford site.



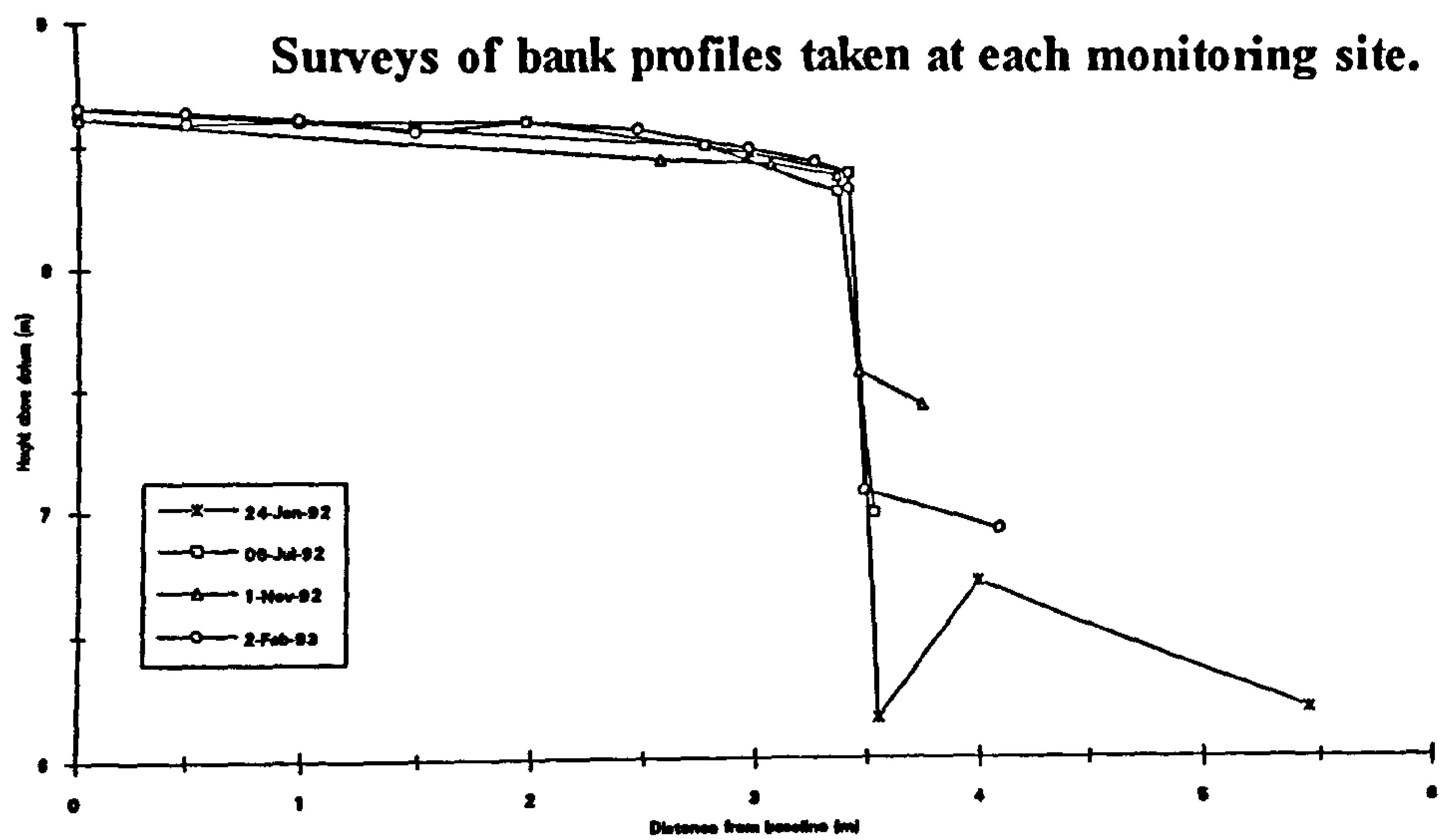
Surveys of the bank at profile eight of the Lower Wallingford site.



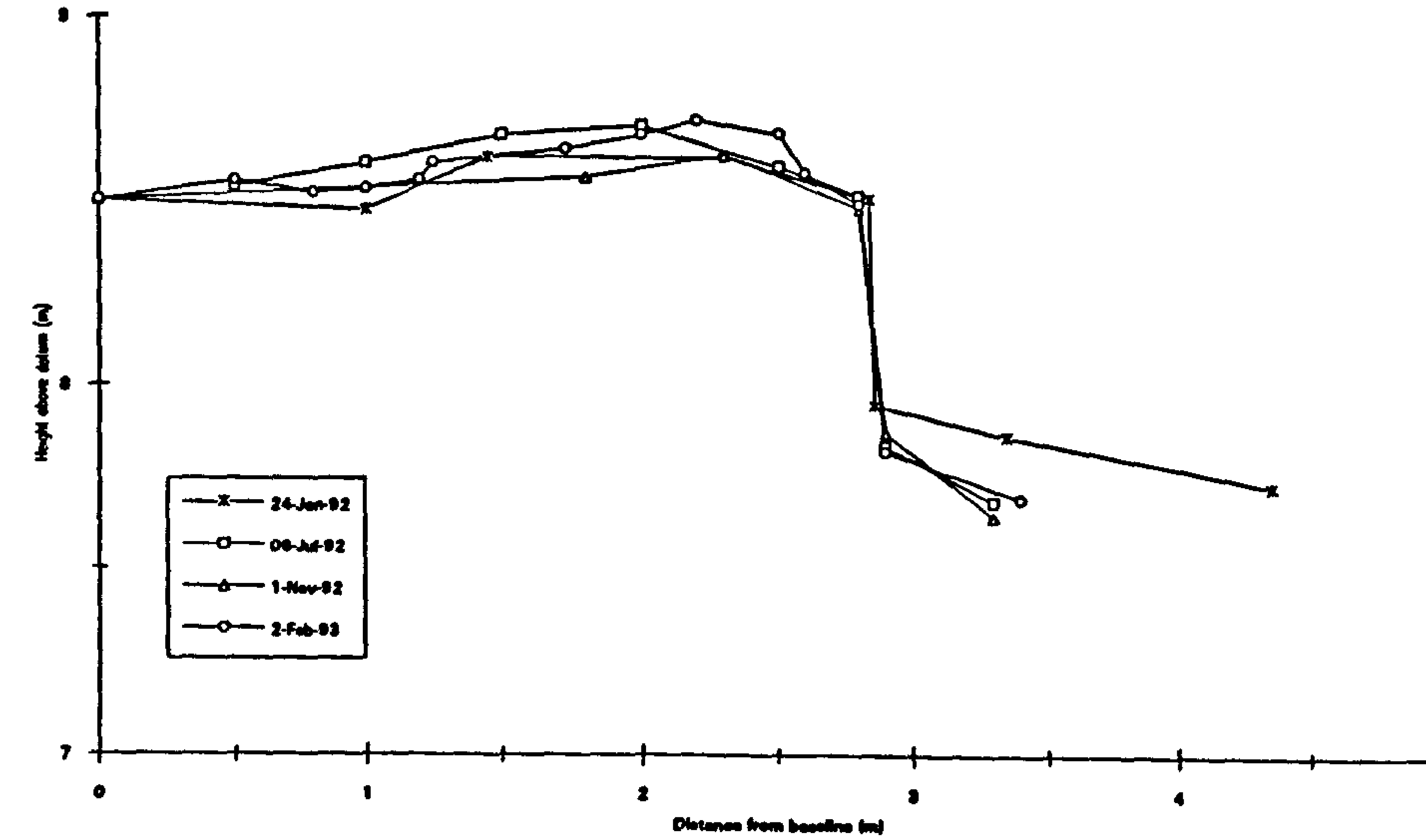
Survey of the bank at profile one of the Goring site.

Appendix 4.4 Continued

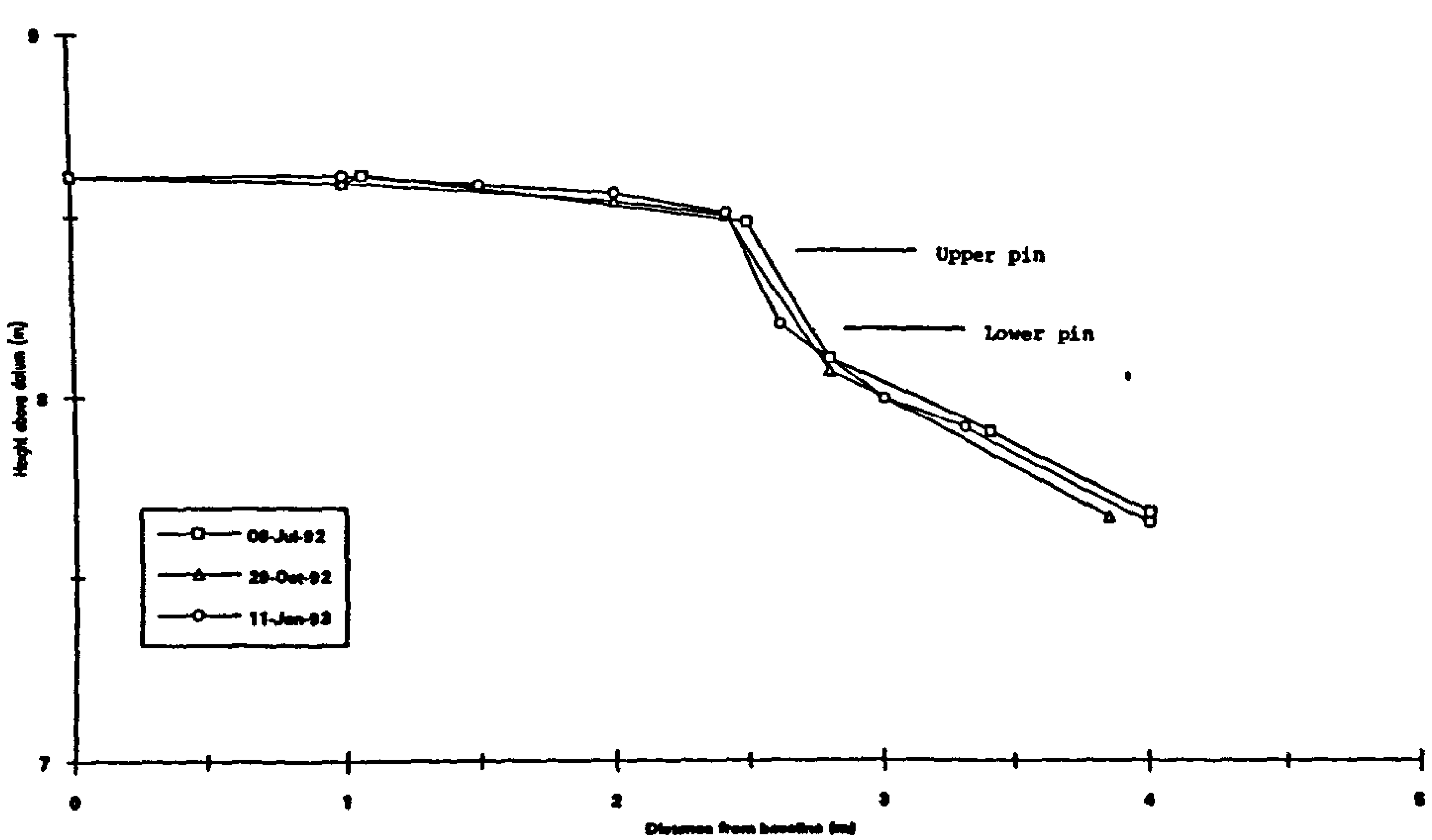
Surveys of bank profiles taken at each monitoring site.



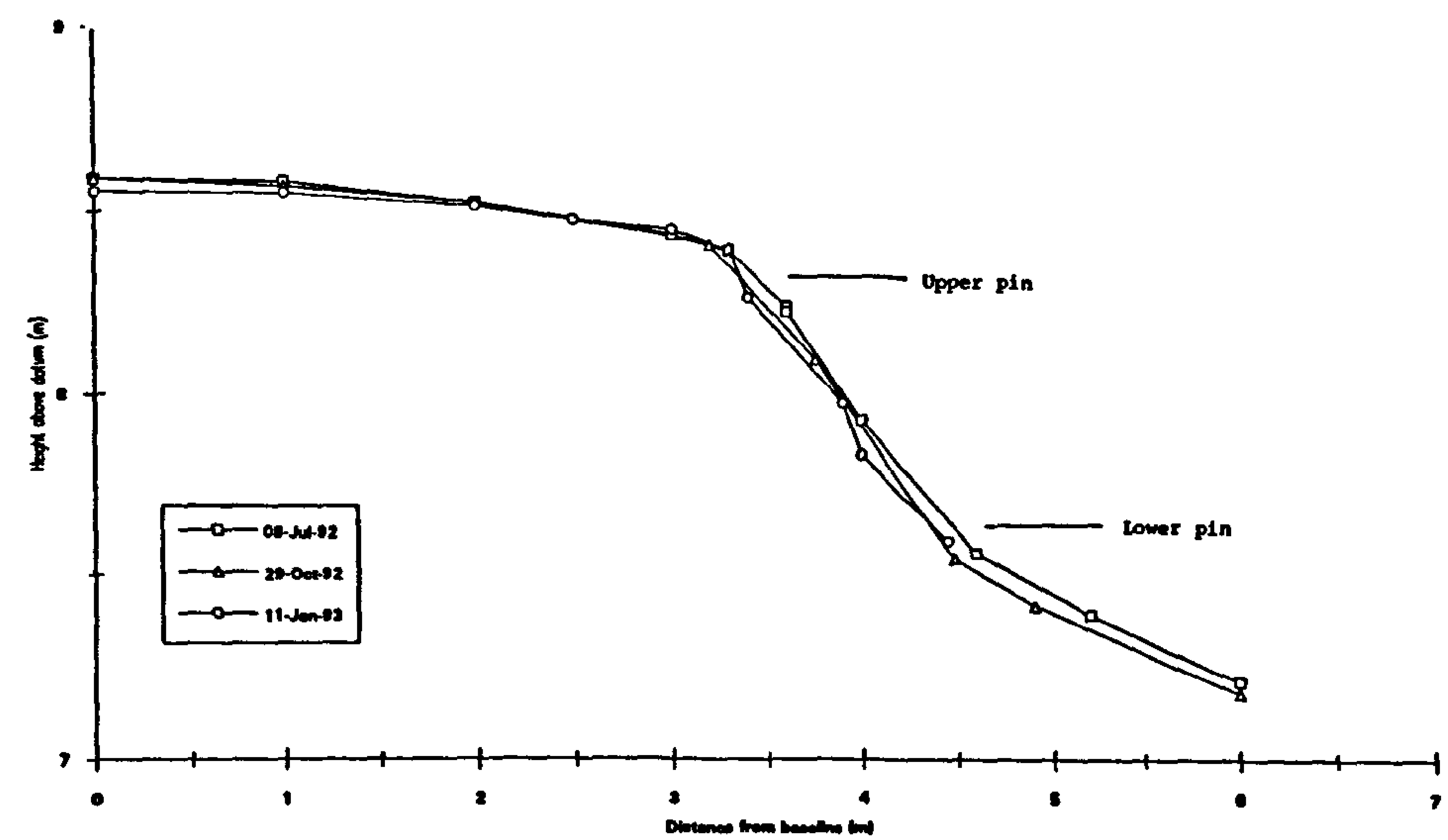
Surveys of the bank at profile two of the Goring site.



Surveys of the bank at profile three of the Goring site.



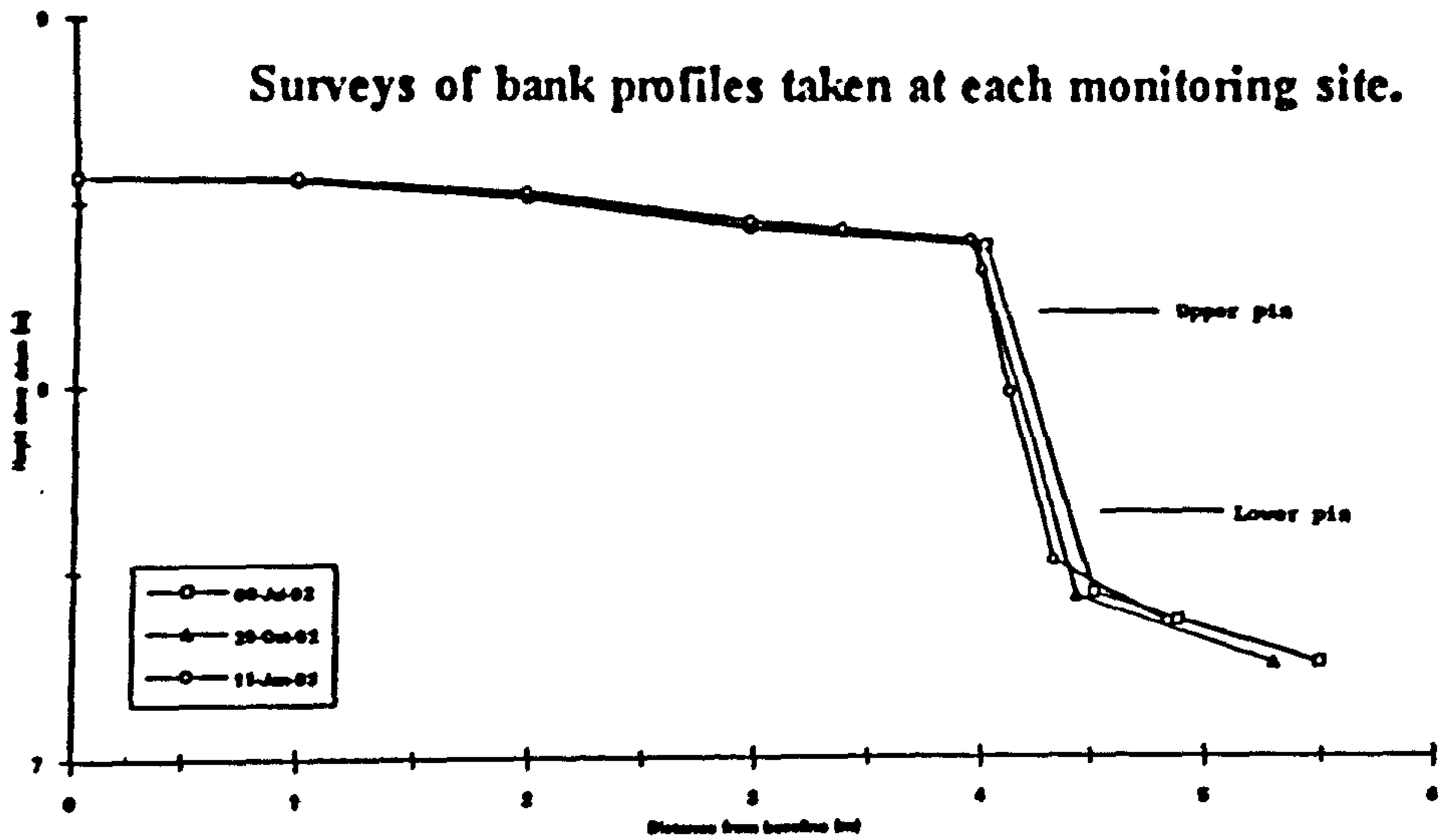
Surveys of the bank at profile one of the Upper Chertsey site.



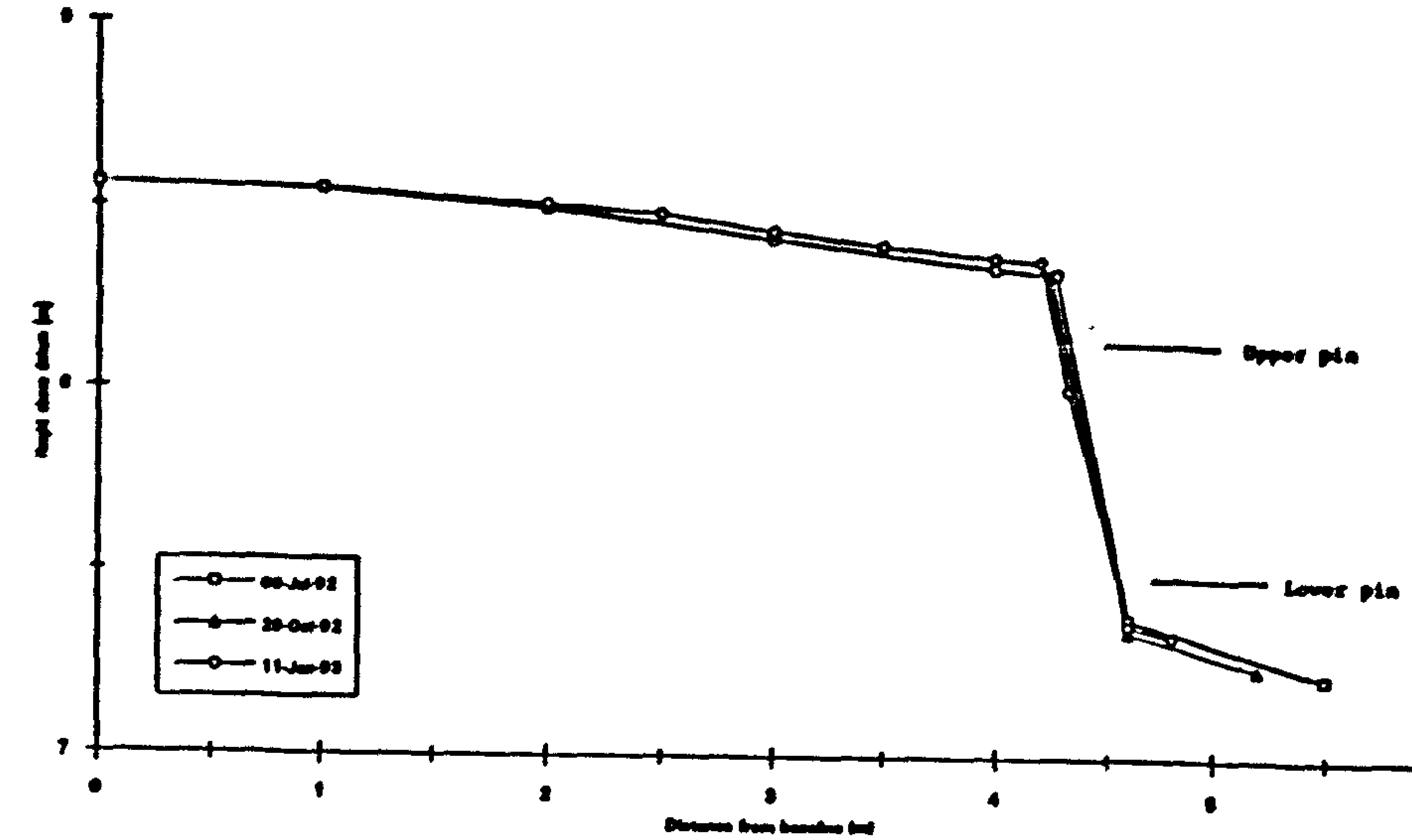
Surveys of the bank at profile two of the Upper Chertsey site.

Appendix 4.4 Continued

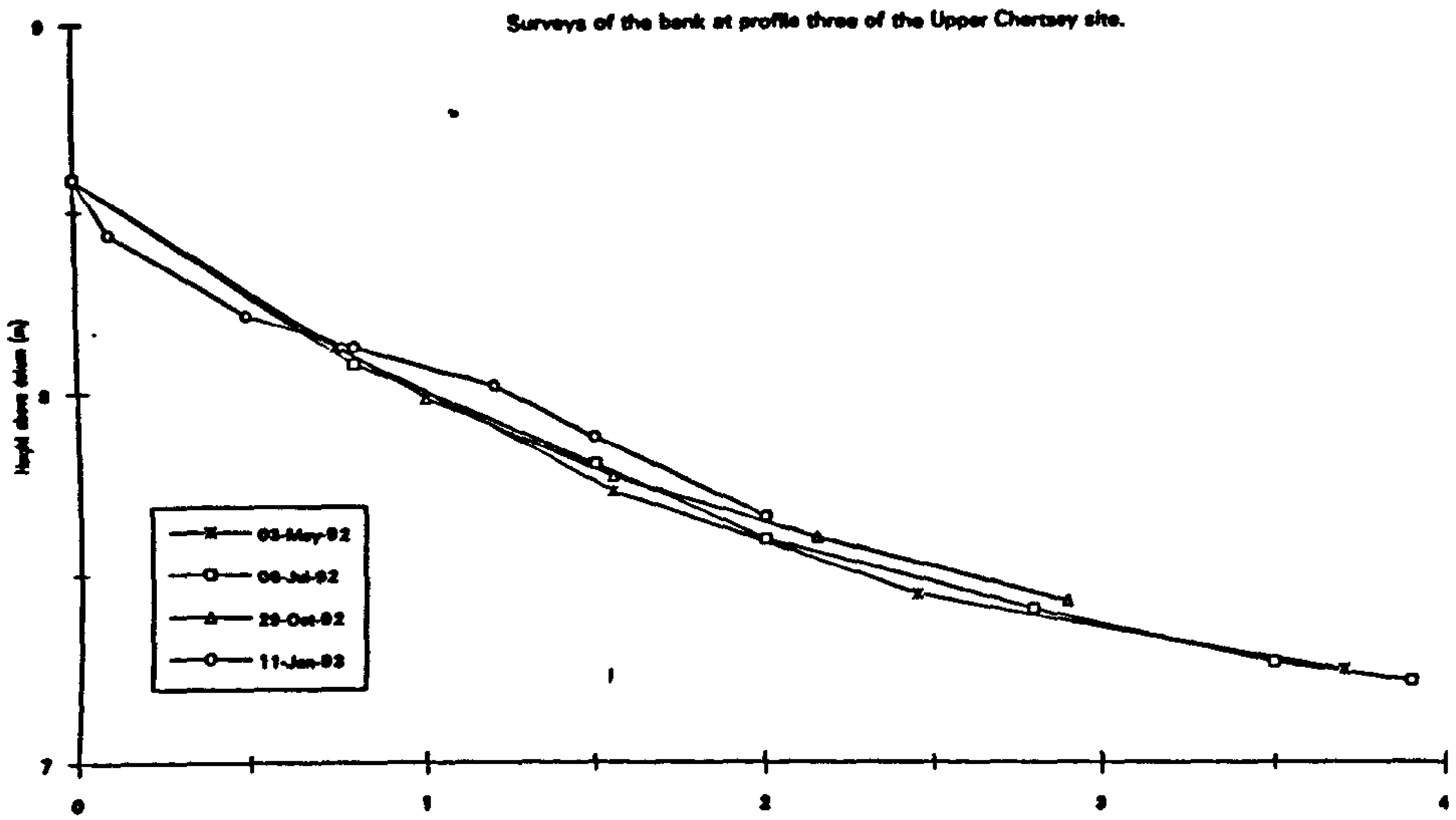
Surveys of bank profiles taken at each monitoring site.



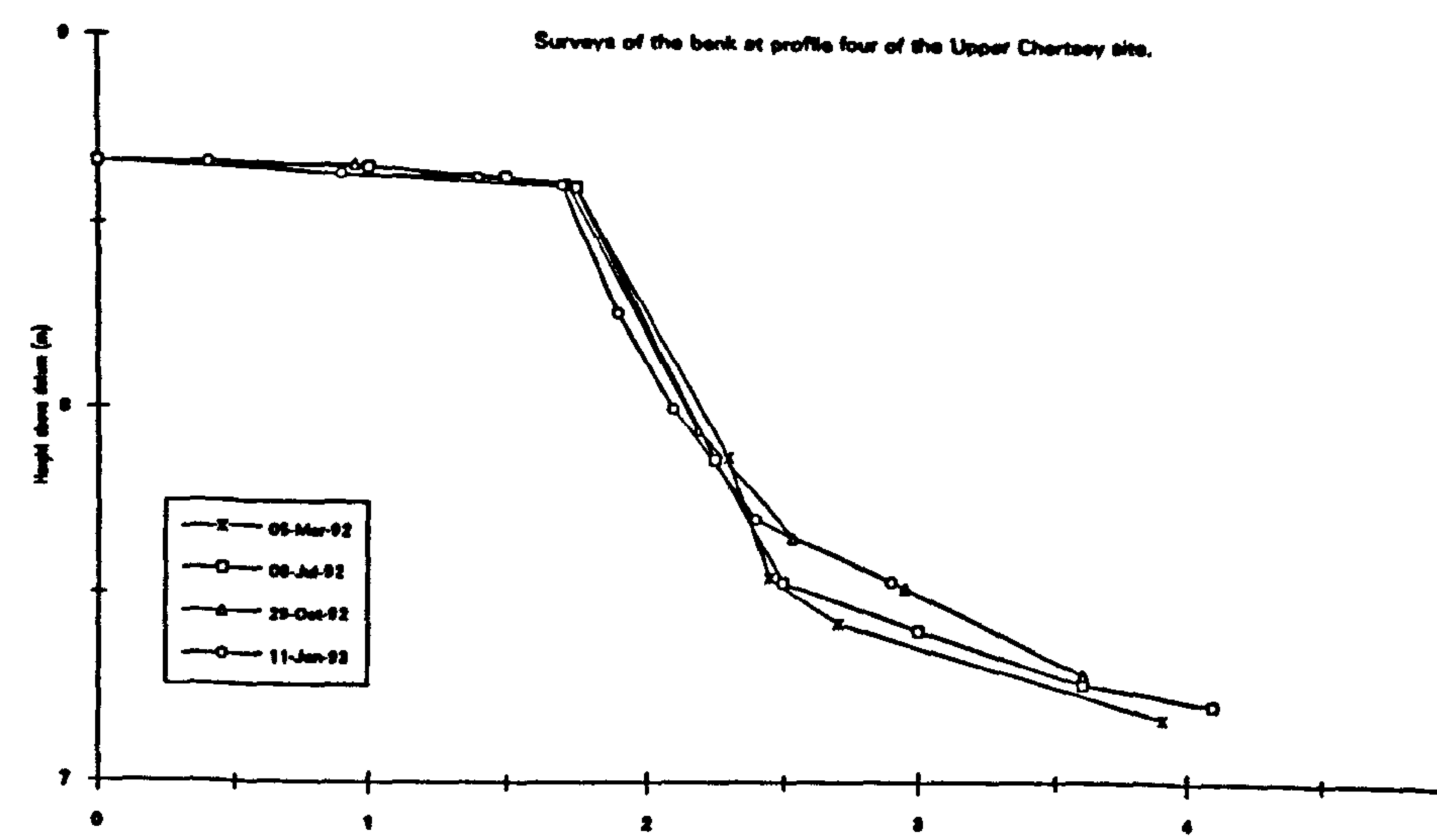
Surveys of the bank at profile three of the Upper Chertsey site.



Surveys of the bank at profile four of the Upper Chertsey site.



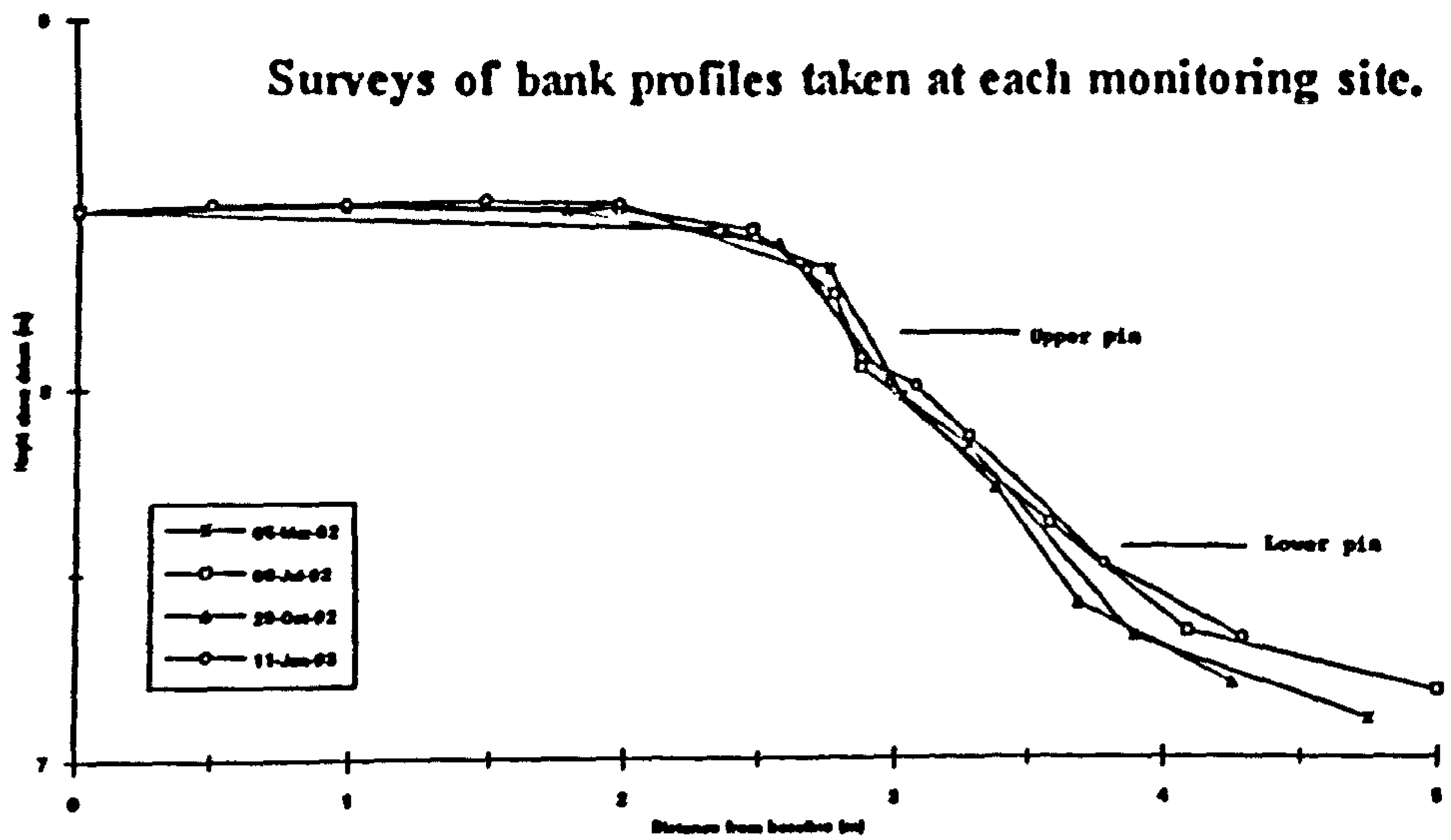
Surveys of the bank at profile one of the Lower Chertsey site.



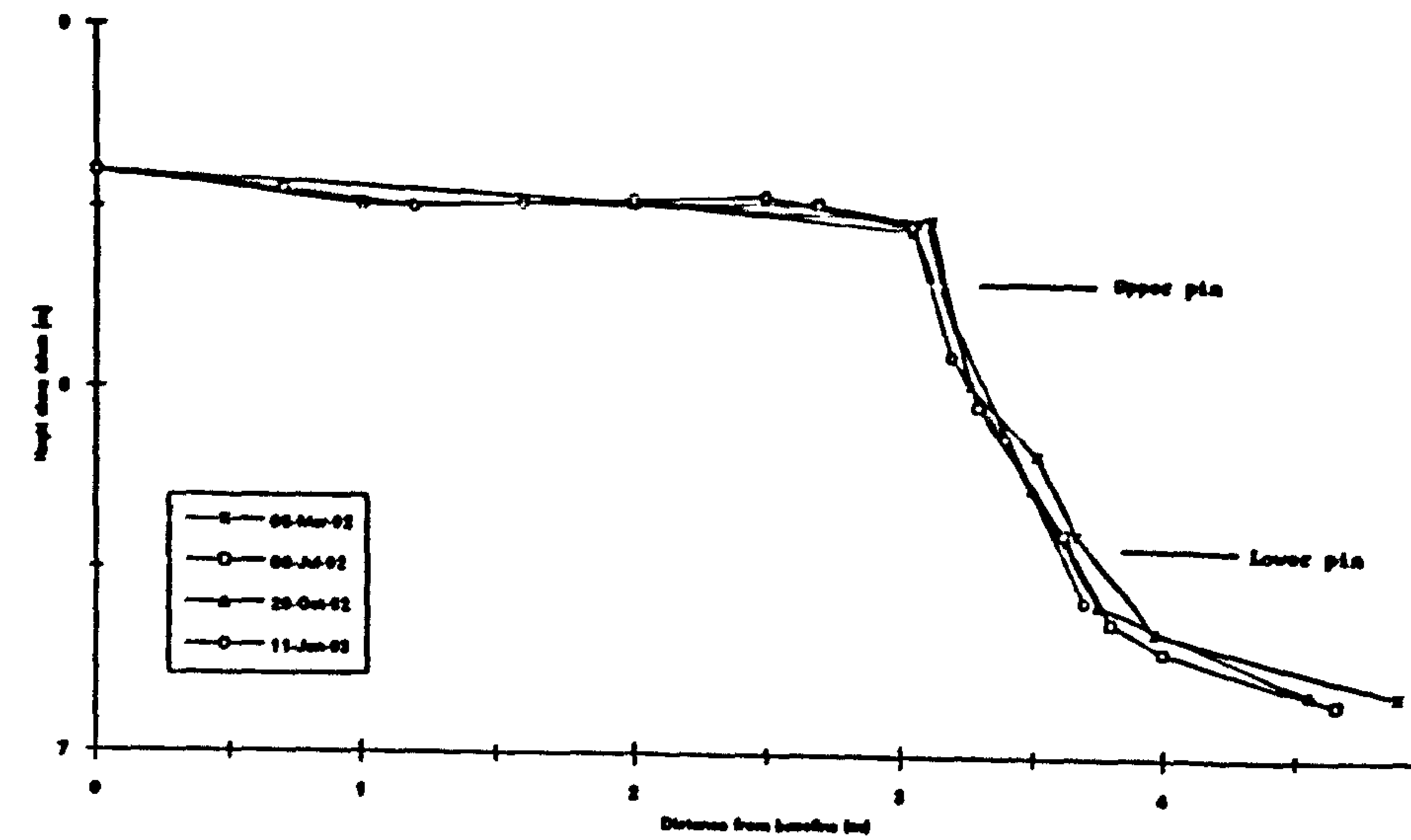
Surveys of the bank at profile two of the Lower Chertsey site.

Appendix 4.4 Continued

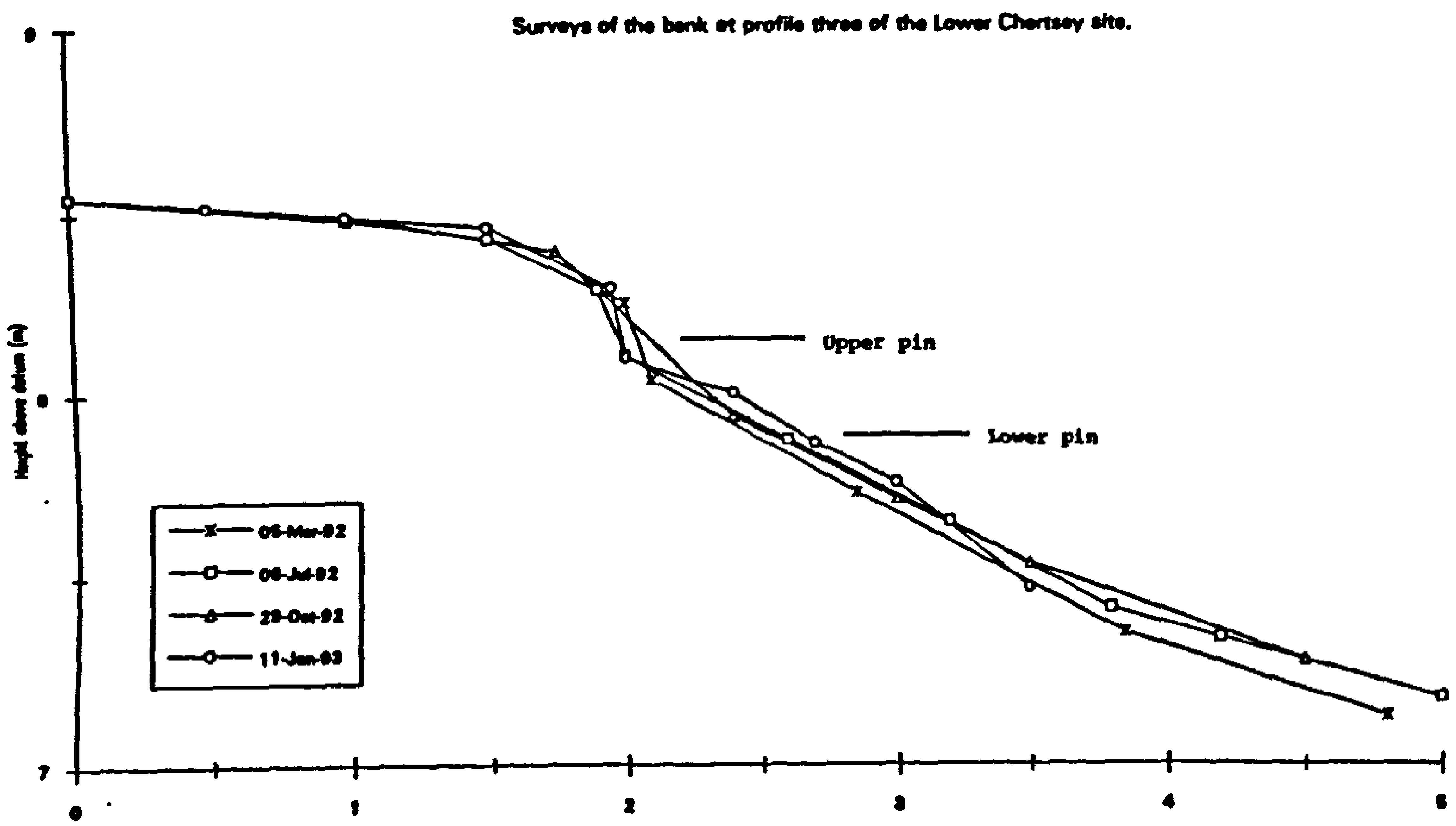
Surveys of bank profiles taken at each monitoring site.



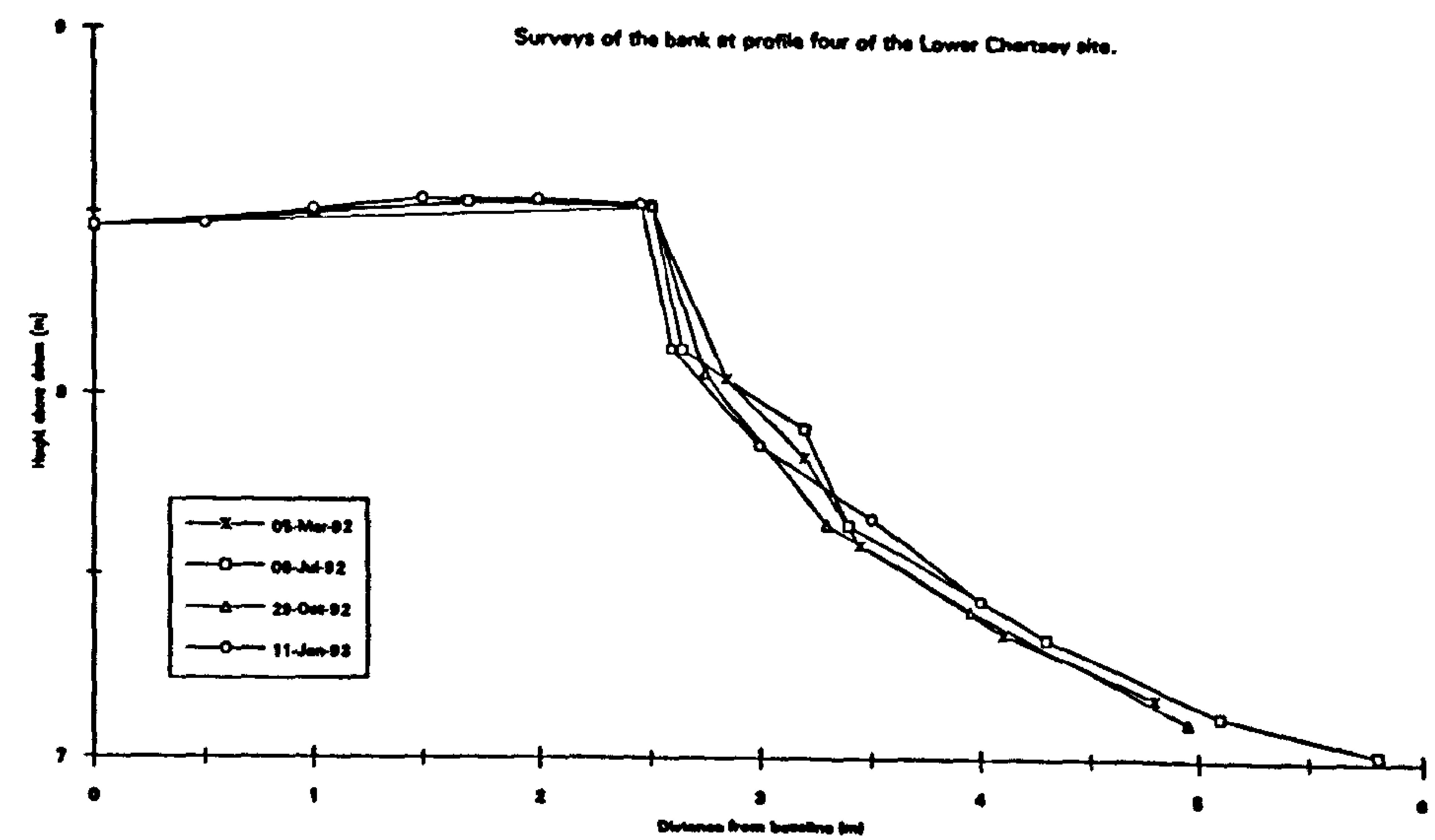
Surveys of the bank at profile three of the Lower Chertsey site.



Surveys of the bank at profile four of the Lower Chertsey site.



Surveys of the bank at profile five of the Lower Chertsey site.



Surveys of the bank at profile six of the Lower Chertsey site.

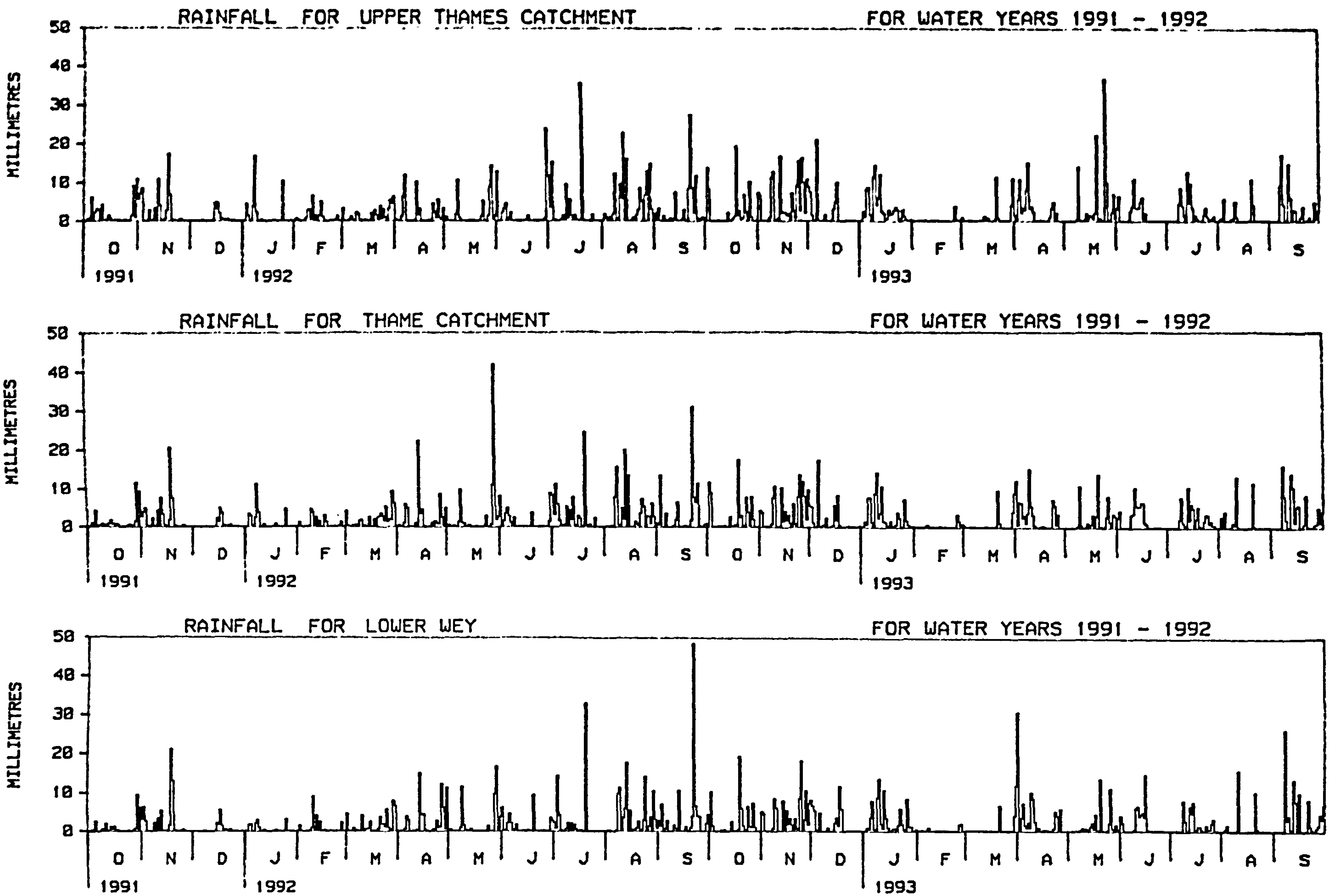
Appendix 4.5 Hydrometric data representative of the bank erosion monitoring sites.

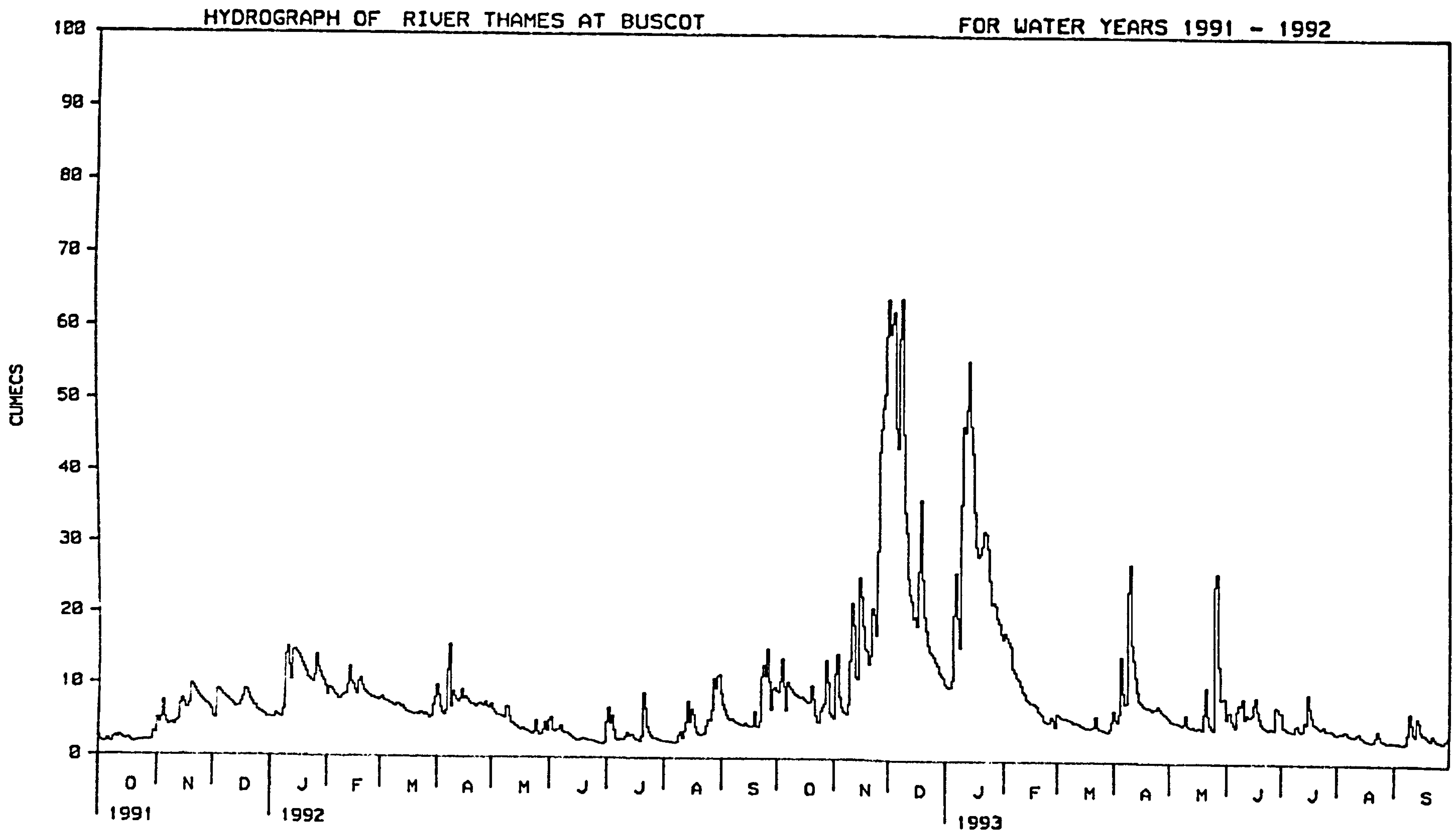
Rainfall and river flow hydrographs (courtesy of Environment Agency, Thames Region) show the conditions during the monitoring period.

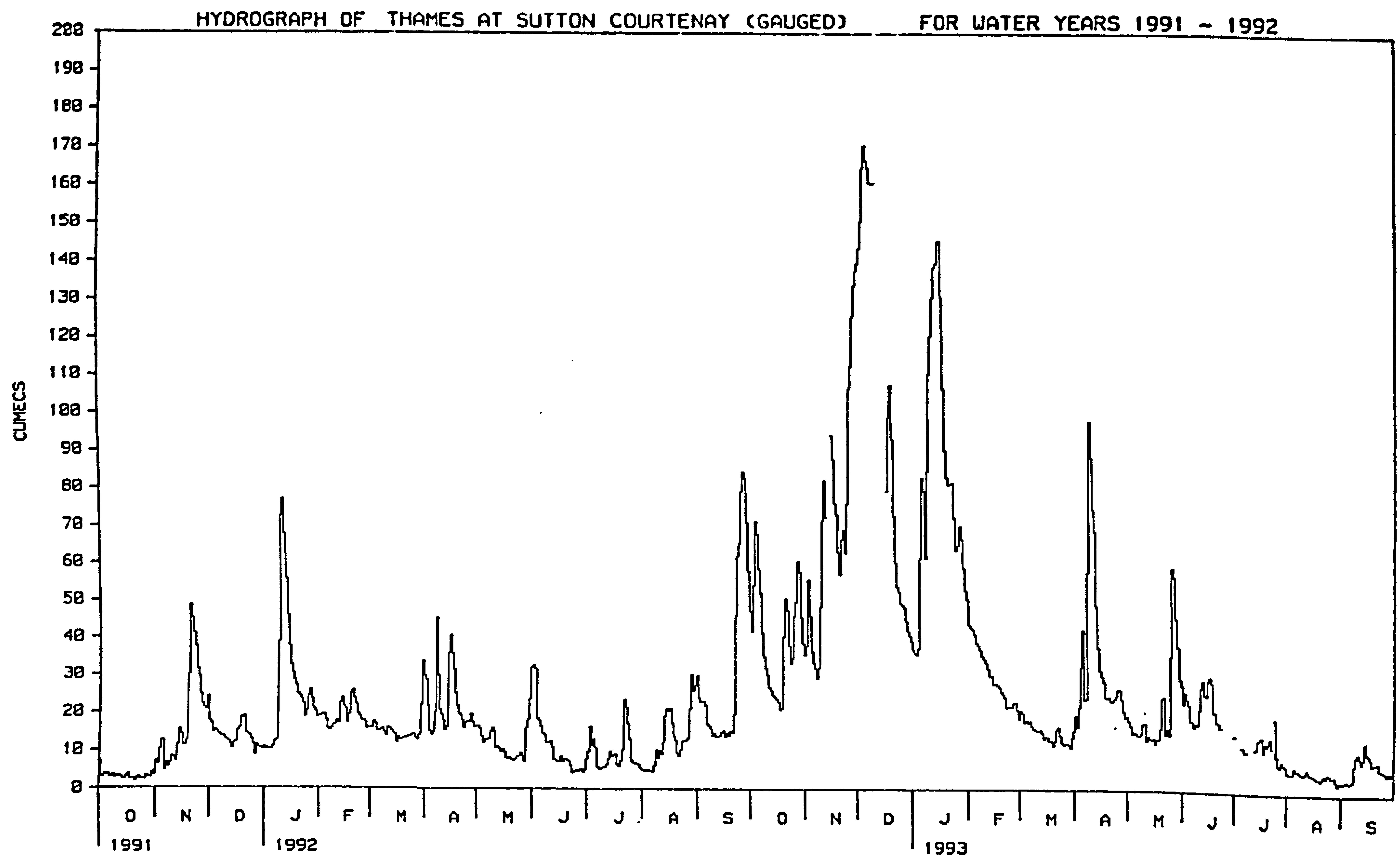
The table below lists the grid references of the flow gauging stations from which discharge hydrographs are shown as representative of discharges at the erosion monitoring sites.

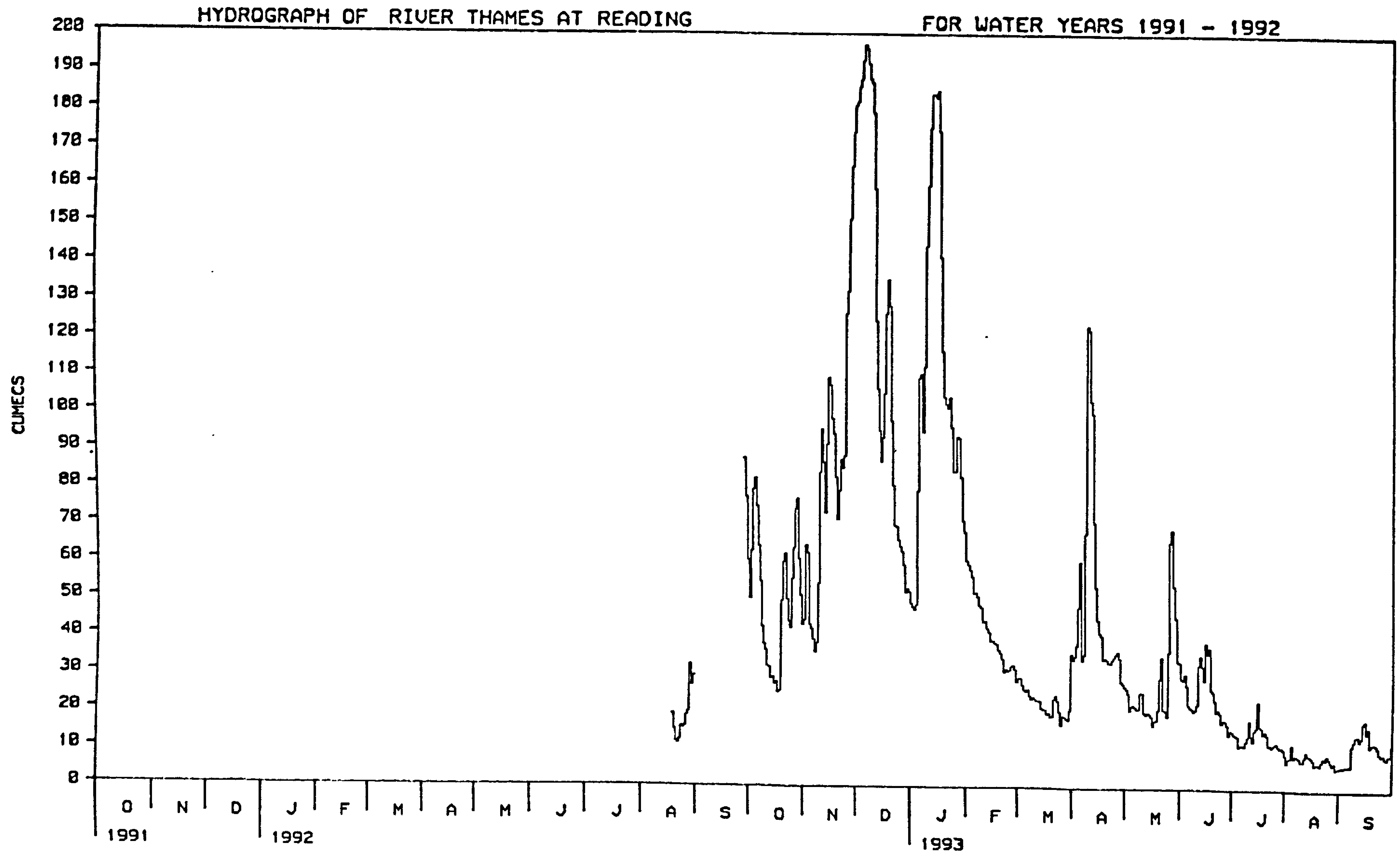
Gauging stations selected for proximity to the erosion monitoring sites.

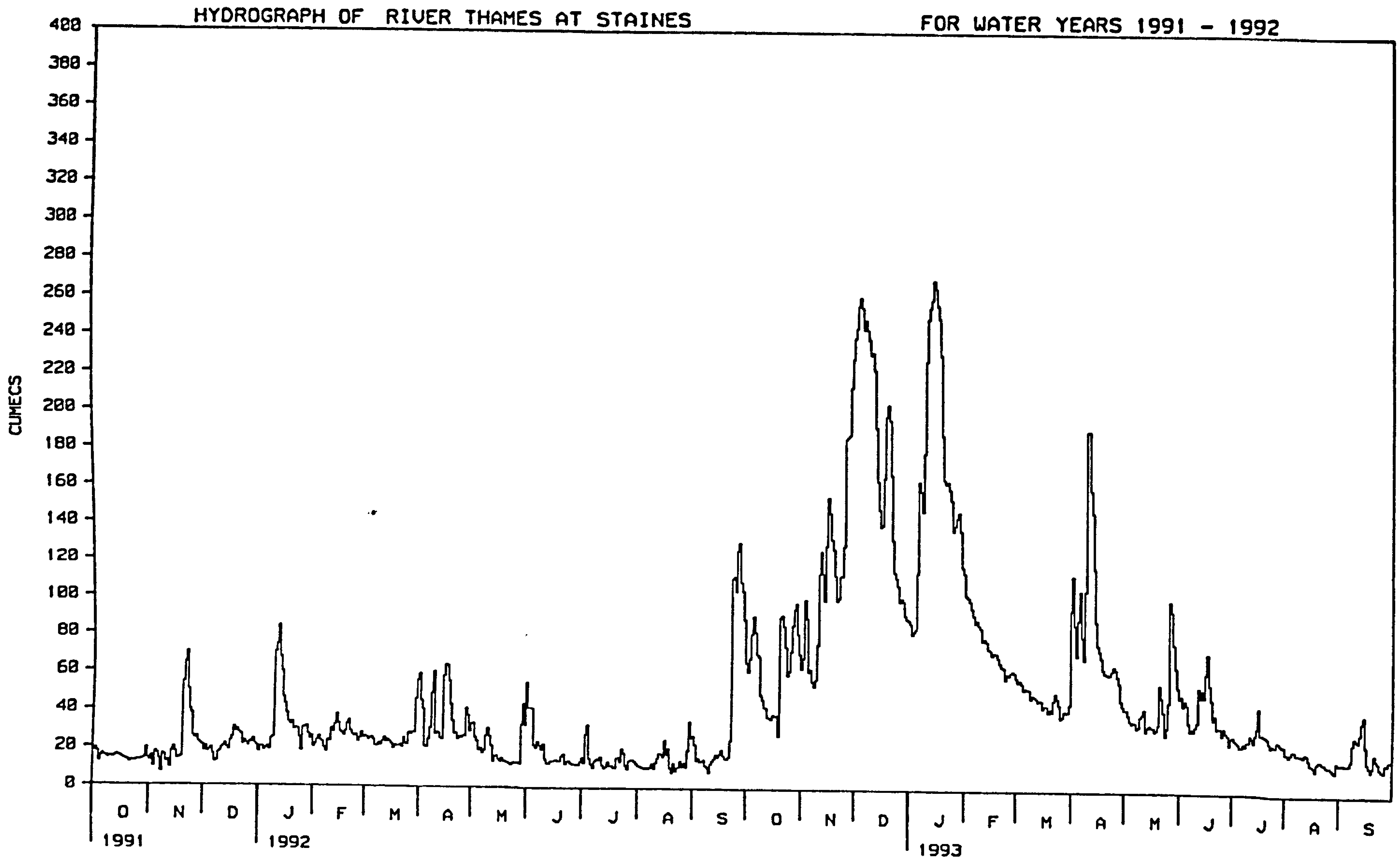
Gauging station NGR	Monitoring site(s)
Buscot SU 230981	St John's
Sutton Courtenay SU 517946	None applicable
Reading SU 718741	Upper & Lower Wallingford Goring
Staines TQ 034714	Laleham Upper & Lower Chertsey


RAINFALL FOR UPPER THAMES CATCHMENT
FOR WATER YEARS 1991 - 1992
MILLIMETRES
50
40
30
20
10
0
O N D J F M A M J J A S O N D J F M A M J J A S
1991
1992
1993
RAINFALL FOR THAME CATCHMENT
FOR WATER YEARS 1991 - 1992
MILLIMETRES
50
40
30
20
10
0
O N D J F M A M J J A S O N D J F M A M J J A S
1991
1992
1993
RAINFALL FOR LOWER WEY
FOR WATER YEARS 1991 - 1992
MILLIMETRES
50
40
30
20
10
0
O N D J F M A M J J A S O N D J F M A M J J A S
1991
1992
1993


HYDROGRAPH OF RIVER THAMES AT BUSCOT
FOR WATER YEARS 1991 - 1992
CUMECS
100
90
80
70
60
50
40
30
20
10
0
O N D J F M A M J J A S O N D J F M A M J J A S
1991
1992
1993


HYDROGRAPH OF THAMES AT SUTTON COURTENAY (GAUGED) FOR WATER YEARS 1991 - 1992
CUMECS
200
190
180
170
160
150
140
130
120
110
100
90
80
70
60
50
40
30
20
10
0
O N D J F M A M J J A S O N D J F M A M J J A S
1991
1992
1993


HYDROGRAPH OF RIVER THAMES AT READING
FOR WATER YEARS 1991 - 1992
CUMECS
200
190
180
170
160
150
140
130
120
110
100
90
80
70
60
50
40
30
20
10
0
O N D J F M A M J J A S O N D J F M A M J J A S
1991
1992
1993


HYDROGRAPH OF RIVER THAMES AT STAINES
FOR WATER YEARS 1991 - 1992
CUMECS
400
380
360
340
320
300
280
260
240
220
200
180
160
140
120
100
80
60
40
20
0
O N D J F M A M J J A S O N D J F M A M J J A S
1991
1992
1993

Appendix 4.6 Boat traffic for the erosion monitoring sites.

The number of craft passing through locks in the vicinity of the erosion monitoring sites was considered a suitable index of the intensity of boat traffic. The locks selected as representative of the monitoring sites are listed below (see Volume III for location of locks).

Thames locks selected for proximity to monitoring sites.

Lock	Monitoring site
St John's	St. John's
Benson	Upper Wallingford Lower Wallingford
Goring	Goring
Chertsey	Laleham Upper Chertsey Lower Chertsey

The table below shows the number of craft passing through each of these locks, respectively during 1992.

Total monthly traffic passing through selected Thames Locks during 1992.

Month	St. John's	Benson	Goring	Chertsey
January	9	30	7	179
February	3	28	21	205
March	36	131	146	345
April	333	1149	1207	2024
May	1004	2164	2332	3887
june	967	2226	2387	3287
July	1292	3478	2766	3957
August	1638	4273	4554	4973
September	701	1998	2138	2728
October	174	517	712	1428
November	11	40	48	325
December	1	3	15	87
Annual total:	6169	16037	16333	23425

APPENDIX 5

Appendix 5.1

Channel geometrey and discharge data for each reach of the River Thames

Reach no.	Reach	Average width (m)	Average depth (m)	Channel centre-line length (m)	Length of valley axis (m)	Bankfull discharge (cumecs)	Discharge at which surface water slope was derived (cumecs)	Water surface slope (at modelled bankfull discharge)	Lock traffic: 1990-1995 (ave. / year)	Specific stream power (W/m2)	Reach sinuosity	Wash impact potential (boats/yr/m width)
1	Buscot	19.8	1.2	1750	1200	53	55	0.000295	6467	7.8	1.46	326
2	Grafton	22.9	1.6	5375	4200	42	45	0.000209	6367	3.8	1.28	279
3	Radcot	19.8	1.3	3475	2600	41	40	0.000241	6065	4.9	1.34	306
4	Rushey	18.3	1.0	3875	2700	48	50	0.000380	5981	9.8	1.44	327
5	Shifford	18.3	1.1	5875	4100	35	40	0.000213	5683	4.0	1.43	311
6	Northmoor	18.3	1.2	10175	7375	33	35	0.000087	6804	1.5	1.38	372
7	Pinkhill	24.4	1.4	6375	4950	55	60	0.000221	8242	4.9	1.29	338
8	Eynsham	22.9	1.6	2625	1800	58	60	0.000225	7930	5.6	1.46	347
9	King's	29.0	1.9	4525	3725	60	55	0.000215	9043	4.4	1.21	312
10	Godstow	29.0	1.8	1950	1325	70	65	0.000247	9208	5.8	1.47	318
11	Osney	35.1	1.4	4050	3775	50	49	0.000208	11235	2.9	1.07	321
12	Iffley	35.1	1.8	3725	3475	55	64	0.000351	13671	5.4	1.07	390
13	Sandford	48.8	2.1	2175	1925	65	63	0.000248	13856	3.2	1.13	284
14	Abingdon	38.1	2.4	7875	7375	105	108	0.000278	15113	7.5	1.07	397
15	Culham	42.7	2.0	3775	3250	145	139	0.000289	15094	9.6	1.16	354
16	Clifton	41.1	1.5	4325	4075	130	131	0.000233	14573	7.2	1.06	354
17	Day's	38.1	1.8	6900	5600	105	105	0.000247	16919	6.7	1.23	444
18	Benson	41.1	2.3	6700	5400	130	140	0.000185	16774	5.7	1.24	408
19	Cleeve	45.7	2.3	10550	10125	160	160	0.000179	18351	6.1	1.04	401
20	Goring	47.2	2.6	1000	1000	140	140	0.000158	18081	4.6	1.00	383
21	Whitchurch	50.3	2.0	6600	6300	145	140	0.000169	21705	4.8	1.05	432
22	Mapledurham	57.9	2.2	3750	3600	145	145	0.000123	22540	3.0	1.04	389
23	Caversham	56.4	2.3	7125	6625	175	165	0.000261	23026	7.9	1.08	408
24	Sonning	57.9	2.3	4425	3775	165	165	0.000166	22257	4.6	1.17	384
25	Shiplake	53.3	2.1	4675	3850	155	160	0.000209	24014	6.0	1.21	450
26	Marsh	57.9	1.9	4325	3500	180	180	0.000194	27376	5.9	1.24	473
27	Hambledon	76.2	2.5	5625	5425	260	220	0.000173	25867	5.8	1.04	339
28	Hurley	71.6	2.5	5150	4625	205	220	0.000189	25849	5.3	1.11	361
29	Temple	71.6	2.3	1725	1650	290	240	0.000206	25184	8.2	1.05	352
30	Marlow	64.0	2.3	2525	2300	105	100	0.000122	25232	2.0	1.10	394
31	Cookham	74.7	2.0	6750	6000	240	240	0.000243	26092	7.6	1.13	349
32	Boulter's	67.1	1.8	4075	3475	260	260	0.000285	27341	10.9	1.17	408
33	Bray	71.6	1.7	3900	3700	240	240	0.000330	26454	10.9	1.05	369
34	Boveney	64.0	1.5	5250	5075	260	260	0.000326	26579	13.0	1.03	415
35	Romney	54.9	2.1	3475	2650	280	280	0.000353	25573	17.7	1.31	466
36	Old Windsor	56.4	1.9	4625	4450	250	250	0.000312	23552	13.6	1.04	418
37	Egham	47.2	1.6	7425	6925	260	260	0.000210	24910	11.3	1.07	527
38	Penton Hook	50.3	2.0	4850	4250	260	260	0.000208	24950	10.6	1.14	496
39	Chertsey	54.9	1.8	3750	2550	250	250	0.000214	24776	9.6	1.47	452
40	Shepperton	54.9	2.0	3325	2500	260	260	0.000235	24895	10.9	1.33	454
41	Sunbury	64.0	2.1	5175	4100	260	260	0.000158	21797	6.3	1.26	341
42	Molesey	79.2	2.1	5300	5225	340	340	0.000122	20482	5.1	1.01	258
43	Teddington	76.2	2.4	7675	7375	340	340	0.000081	16170	3.5	1.04	212

Appendix 5.2

Bank protection and vegetation characteristics along each reach of the River Thames

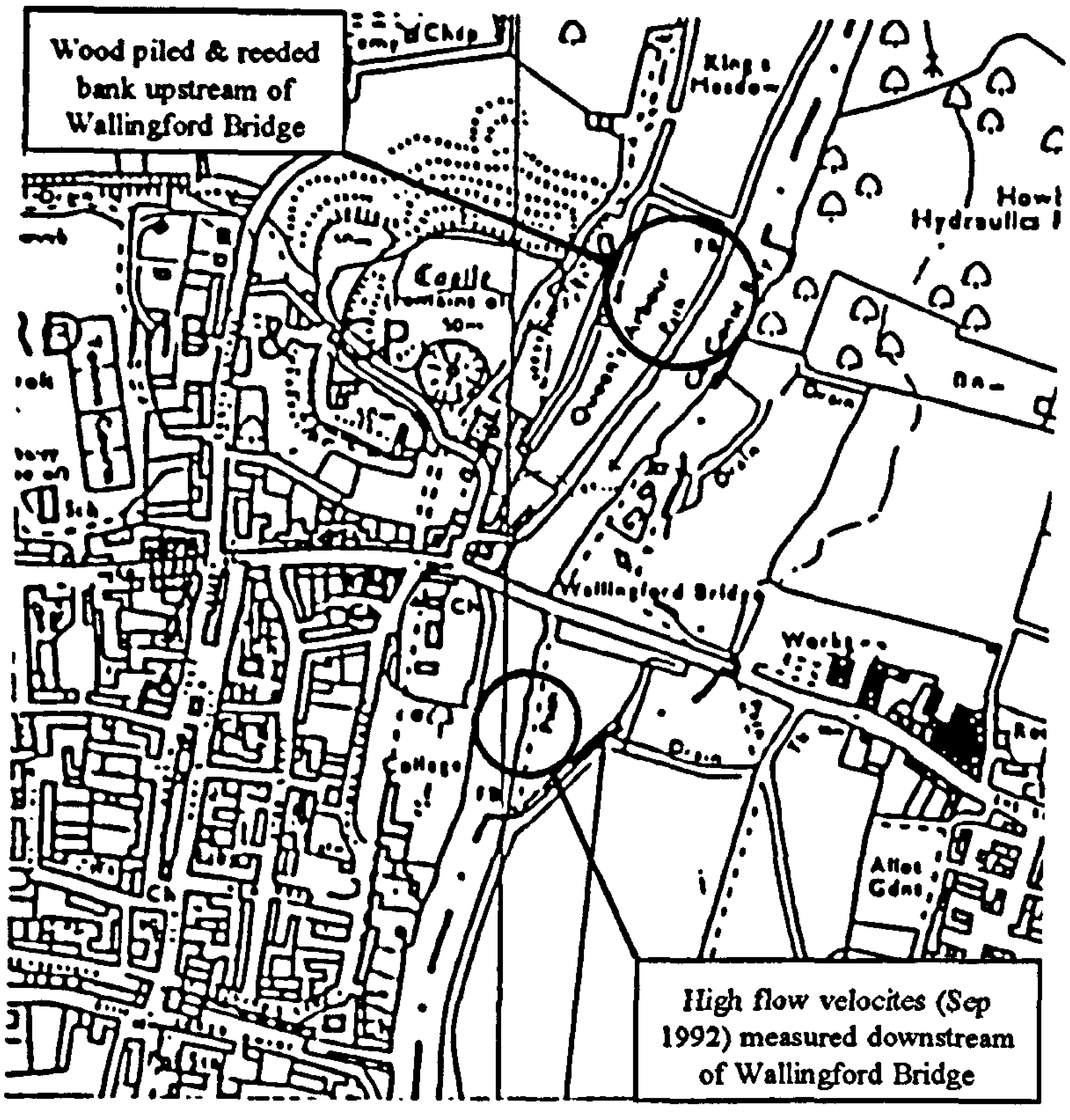
(all measurements in metres)

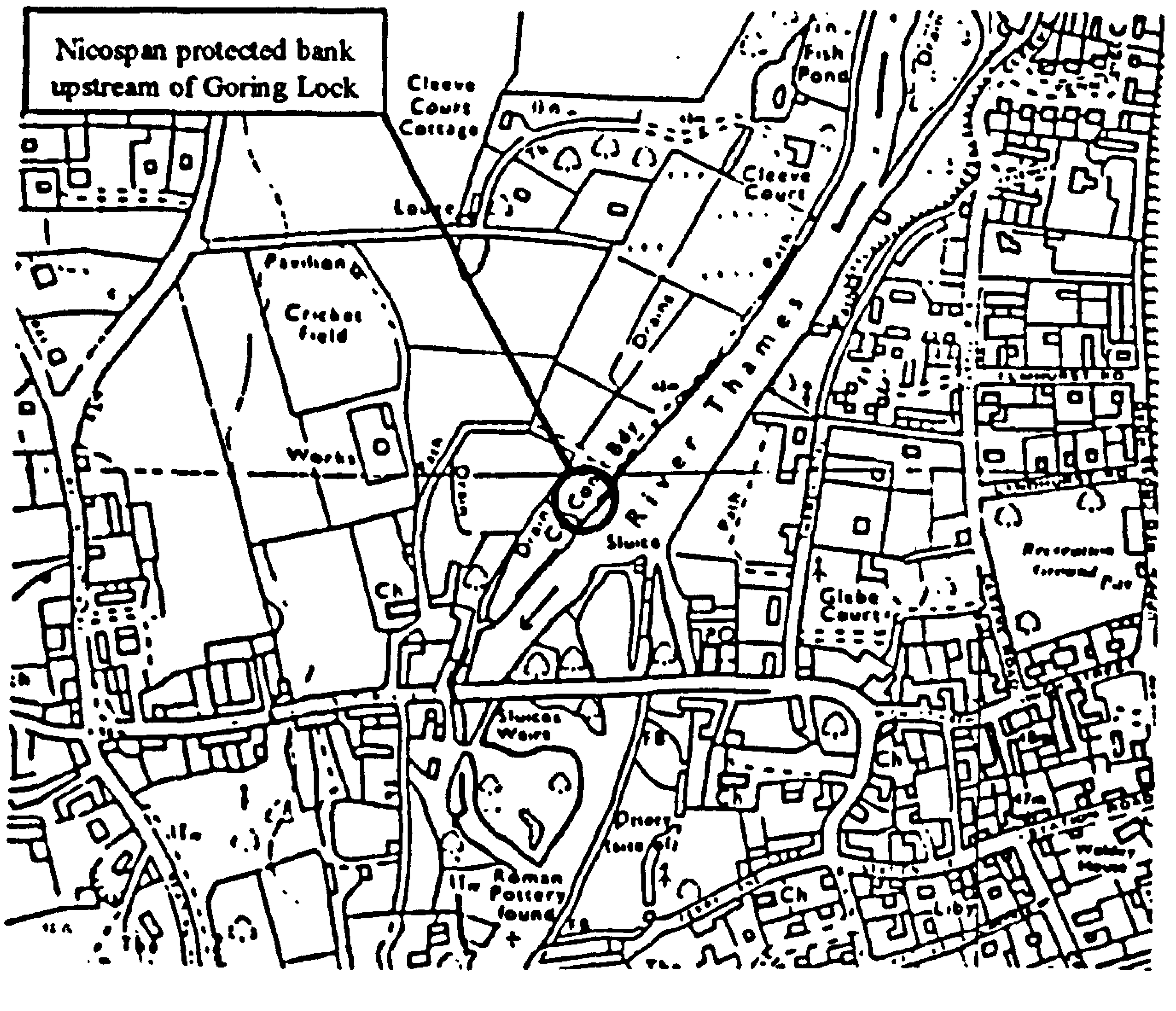
		Intact hard bank protection				Failing hard bank protection						Vegetation at unprotected river bank						'Soft' protection				
Reach no.	Reach	Sheet piling	Bagwork	Concrete/masonry	Brickwork	Sheet piling	Bagwork	Concrete/masonry	Brickwork	Total length of intact hard protection	Total length of failing hard protection	Grass	Shrubs	Trees	Wooded	Earth	Unsurveyed bank	Intact	Failing	Total length of hard bank protection	Total length surveyed	Deflection potential
1	Buscot	0	0	30	0	0	0	0	0	30	0	0	2750	60	0	170	150	0	0	30	3010	0.01
2	Grafton	60	20	0	0	0	0	0	0	80	0	1220	7320	1090	400	1890	0	0	0	80	12000	0 01
3	Radcot	113	38	13	38	0	13	0	0	202	13	529	3766	2320	60	570	0	0	0	215	7460	0 03
4	Rushey	50	0	0	0	0	0	0	0	50	0	2620	3550	250	50	1300	100	0	0	50	8020	0 01
5	Shifford	100	0	0	0	0	0	0	0	100	0	1450	7610	1550	760	1235	300	0	0	100	12725	0.01
6	Northmoor	220	0	0	40	0	0	20	0	260	20	4070	6700	3730	480	255	310	0	0	280	15515	0 02
7	Pinkhill	30	75	80	0	0	35	0	0	185	35	970	4590	4260	1130	270	960	0	0	220	11440	0 02
8	Eynsham	210	20	70	0	0	0	0	0	300	0	10	3570	150	210	180	420	0	0	300	4420	0.07
9	Kings	260	0	20	0	0	0	0	0	280	0	460	4770	1870	740	310	100	13	0	280	8443	0.03
10	Godstow	135	360	20	0	0	110	0	0	515	110	320	1475	790	100	160	400	0	230	625	3700	0.17
11	Osney	570	1290	85	30	0	230	100	50	1975	380	2460	320	2360	620	390	100	38	0	2355	8543	0.28
12	Iffley	850	1850	510	400	0	500	0	130	3610	630	430	480	990	1360	30	20	0	0	4240	7530	0 56
13	Sandford	570	420	0	155	0	15	0	0	1145	15	1285	410	1265	900	120	230	75	0	1160	5215	0.22
14	Abingdon	210	240	0	0	0	100	0	0	450	100	300	4780	2870	4810	180	1100	0	0	550	13490	0.04
15	Culham	1990	1540	370	40	0	250	200	0	3940	450	390	900	1510	310	270	230	0	0	4390	7770	0.56
16	Clifton	370	250	0	0	0	260	0	0	620	260	970	1280	2410	1620	650	1600	0	0	880	7810	0.11
17	Days	650	50	0	0	0	0	0	0	700	0	3940	700	1800	1900	1220	280	0	0	700	10260	0.07
18	Benson	1130	140	0	300	0	0	0	0	1570	0	1990	3040	2940	2890	810	370	0	0	1570	13240	0.12
19	Cleeve	2720	400	270	100	0	0	0	0	3490	0	2400	4300	3160	7030	1550	200	0	0	3490	21930	0.16
20	Goring	550	20	0	0	0	0	0	0	570	0	300	100	530	450	0	300	275	125	570	2350	0.24
21	Whitchurch	1250	65	0	0	80	0	0	0	1315	80	2315	1055	895	6680	230	90	90	60	1395	12920	0.11
22	Mapledurham	160	40	0	0	0	50	0	0	200	50	1640	550	900	2930	600	210	13	0	250	7083	0.04
23	Caversham	3890	2755	0	90	200	40	0	0	6735	240	440	210	870	4575	80	670	0	0	6975	13150	0.53
24	Sonning	1470	1120	70	0	50	60	0	0	2660	110	40	1380	560	2950	190	440	0	0	2770	7910	0.35
25	Shiplake	1080	360	150	0	0	50	30	0	1590	80	510	1800	1140	2550	430	310	0	0	1670	8100	0.21
26	Marsh	3070	360	150	0	50	50	30	0	3660	130	200	1550	680	1530	350	100	0	0	3990	8300	0 48
27	Hambledon	4170	390	20	200	200	60	50	0	4780	310	240	1200	1020	1540	390	590	125	0	5090	9605	0.53
28	Hurley	195	340	90	0	0	100	0	0	625	100	1700	750	635	6140	530	360	0	0	725	10480	0.07
29	Temple	480	540	170	0	0	120	0	0	1190	120	40	30	0	110	0	510	0	0	1310	1490	0 88
30	Marlow	2080	320	610	240	0	40	30	0	3230	70	0	200	970	600	40	90	13	125	3300	5248	0 63
31	Cookham	5330	280	680	125	0	40	150	0	6415	190	660	600	2280	2045	680	1230	0	0	6605	12870	0 51
32	Boulters	1570	130	10	0	60	0	10	0	1710	70	420	220	370	2750	110	400	13	0	1780	5663	0 31
33	Bray	2910	85	240	0	0	0	0	0	3235	0	200	70	100	650	20	1900	675	0	3235	4950	0 65
34	Boveney	1300	210	310	0	0	0	70	0	1820	70	370	310	1090	4280	190	1500	0	0	1890	8130	0.23
35	Romney	1840	835	605	270	60	390	200	0	3550	650	450	110	165	1475	340	150	0	0	4200	6740	0 62
36	Old Windsor	3945	965	80	0	0	220	30	0	4990	250	0	180	1960	2530	140	200	0	0	5240	10050	0 52
37	Egham	2430	1100	830	0	0	130	30	0	4360	160	470	330	70	2120	70	850	225	125	4520	7930	0 57
38	Penton Hook	3950	1050	1740	30	20	100	80	0	6770	200	690	40	260	610	60	0	0	15	6970	8645	0.81
39	Chertsey	1620	2290	120	0	0	220	10	0	4030	230	160	0	500	950	90	0	0	0	4260	5960	0.71
40	Shepperton	1100	560	80	40	0	210	0	0	1780	210	440	260	650	400	240	2250	170	0	1990	4150	0 48
41	Sunbury	1360	2010	1120	0	0	180	50	0	4490	230	1510	50	140	470	0	1900	0	0	4720	6890	0 69
42	Molesey	2630	3170	520	1020	20	620	10	60	7340	710	960	0	20	50	120	280	0	0	8050	9200	0.88
43	Teddington	5620	3155	1810	1500	0	1385	190	0	12085	1575	0	0	0	0	20	700	0	0	13660	13680	1 00

NB: 'soft' prootection = gabions, geotextiles and spiling

Appendix 5.3 Boat wash monitoring and bank shear stress data.

The locations of the sites at which boat wash and flow velocities were measured are shown below.





Velocities near to the bank upstream of Wallingford Bridge were measured during the high flows on 29 September 1992, when discharge was estimated at approximately 100m^3/s. The maximum near-bank velocities recorded during each minute time period over a period of ten minutes are shown below:

Time period (minute)	Maximum near-bank velocity, Vmax (m/s)
1	0.123
2	0.164
3	0.121
4	0.059
5	0.092
6	0.103
7	0.079
8	0.103
9	0.108
10	0.080
Mean	0.103
Maximum	0.164

Near-bank shear stresses can be calculated using the formula:

$$\tau_b = \rho(uK)^2 / (\ln(z/z_o))^2$$

and substituting the maximum near-bank velocity recorded on 29 September 1992 (0.164 m/s) for u,

$$\tau_b = 1.66 \text{ N/m}^2$$

Appendix 5.3 continued : Boat wash monitoring statistics

Site 1: Wallingford - Upstream of Wallingford Bridge
Monitored at a sheet piled bank on 8th August 1992 (average channel velocity = 1.9cm/s)

Time	Direction U/D	Boat Type S/M/L/B	Boat Velocity (m/s)	Boat Velocity (mph)	Boat Velocity (km/hr)	Drawdown (cm)	Elevation (cm)	Wave Height (cm)	Max. Velocity (cm/s)	Max. Velocity (m/s)	Sailing position (1/2/3/4/M)
10.00	D	L	0.83	1.86	3.00	2.5	2.2	4.7			2
10.01	D	S	0.91	2.03	3.27	1.2	3.2	4.4			2
10.12	U	L	1.00	2.24	3.60	6	7.6	13.6			M
10.22	U	L	1.00	2.24	3.60	3	4.2	7.2			M
10.24	D	M	1.00	2.24	3.60	2.4	6	8.4			M
10.26	U	M	0.77	1.72	2.77	2	2.7	4.7			M
10.38	U	L	0.77	1.72	2.77	4.8	5.2	10			3
10.44	U	M	0.91	2.03	3.27	2.4	4.2	6.6			3
10.56	U	S	0.71	1.60	2.57	2.4	3.7	6.1			3
10.57	D	S	0.91	2.03	3.27	2.4	4.7	7.1			M
10.59	D	M	0.83	1.86	3.00	2.4	4.7	7.1			M
11.16	D	M	1.11	2.49	4.00	6	7.6	13.6			M
11.17	D	M	0.83	1.86	3.00	6	8.7	14.7			M
11.17	D	M	1.11	2.49	4.00	2.4	4.2	6.6			M
11.24	U	M	0.23	0.52	0.84	1.2	1.2	2.4			M
11.30	U	M	0.63	1.40	2.25	2	2.2	4.2			3
11.32	D	L	1.25	2.80	4.50	4.6	8.7	13.3			M
11.33	D	L	0.83	1.86	3.00	4.6	5.7	10.3			3
11.39	U	M	0.83	1.86	3.00	4.6	4.2	8.8			3
11.43	U	M	0.91	2.03	3.27	4.7	6.5	11.2			M
11.44	D	M	1.25	2.80	4.50	6	11.2	17.2			2
11.45	D	M	0.83	1.86	3.00	3.5	8.7	12.2			M
11.47	U	M	0.71	1.60	2.57	6	7.7	13.7			M
12.00	U	M	0.83	1.86	3.00	4.7	7.7	12.4			M
12.01	U	M	0.91	2.03	3.27	2.4	8.3	10.7			M
12.08	D	M	1.11	2.49	4.00	6	6.5	12.5			M
12.09	U	M	1.00	2.24	3.60	1.2	1.2	2.4			4
12.13	U	L	0.83	1.86	3.00	4.7	6.5	11.2			3
12.19	U	M	1.00	2.24	3.60	2.4	4.2	6.6			M
12.37	D	M	1.00	2.24	3.60	4.7	10	14.7			3
12.39	D	B	1.25	2.80	4.50	4.7	6.5	11.2			M
12.42	U	M	0.91	2.03	3.27	6	13.7	19.7			M
12.42	U	M	1.43	3.20	5.14	6	13.7	19.7			2
12.51	U	M	0.91	2.03	3.27	2.4	5.7	8.1			3
12.56	D	M	1.43	3.20	5.14	2.4	10	12.4			M
12.57	D	M	1.43	3.20	5.14	3.5	10	13.5			2
12.58	U	S	1.72	3.86	6.21	12	27	39			3
13.00	D	S	1.00	2.24	3.60	1.2	16	17.2			M
13.17	U	M	0.83	1.86	3.00	1.2	3.2	4.4			3
13.18	D	S	1.00	2.24	3.60	1.2	3.2	4.4			2
13.24	U	M	0.77	1.72	2.77	2.4	3.2	5.6			3
13.28	U	M	1.00	2.24	3.60	3.5	5.2	8.7			M
13.38	D	M	0.85	1.91	3.08	6	7.7	13.7	5.4	0.054	3

Site 1: Continued

Time	Direction U/D	Boat Type S/M/L/B	Boat Velocity (m/s)	Boat Velocity (mph)	Boat Velocity (km/hr)	Drawdown (cm)	Elevation (cm)	Wave Height (cm)	Max. Velocity (cm/s)	Max. Velocity (m/s)	Sailing position (1/2/3/4/M)
13.40	D	B	0.90	2.02	3.24	1.2	7	8.2	5.3	0.053	M
13.43	U	M	0.77	1.72	2.77	2	3.2	5.2	4.5	0.045	M
13.58	U	L	0.91	2.03	3.27	1.8	2.2	4	3	0.03	3
14.03	D	M	0.77	1.72	2.77	2.4	3.2	5.6	5.2	0.052	3
14.16	U	L	1.00	2.24	3.60	7.1	5.2	12.3	4.8	0.048	M
14.18	U	L	1.00	2.24	3.60	7.1	6.5	13.6	7.1	0.071	M
14.25	U	B	0.56	1.24	2.00	1.8	2.2	4	2.5	0.025	3
14.40	D	L	0.83	1.86	3.00	3	2.2	5.2	3.3	0.033	M
14.54	D	L	1.00	2.24	3.60	2.4	4.2	6.6	5.2	0.052	3
14.57	D	L	0.45	1.02	1.64	0.8	0	0.8	3.3	0.033	3
14.58	U	S	0.77	1.72	2.77	4.7	7.7	12.4	8.9	0.089	M
15.02	D	S	3.33	7.46	12.00	6	7.7	13.7	5.4	0.054	3
15.04	U	L	0.83	1.86	3.00	2.4	3.7	6.1	4.4	0.044	M
15.06	U	L	0.91	2.03	3.27	6	2.2	8.2	4.7	0.047	3
15.08	U	S	1.00	2.24	3.60	9.5	17.2	26.7	4.8	0.048	M
15.11	U	M	0.91	2.03	3.27	3	4.7	7.7	3.4	0.034	3
15.13	D	M	0.71	1.60	2.57	1.2	3.2	4.4	4.6	0.046	M
15.14	D	M	0.63	1.40	2.25	3.5	2.2	5.7	3.4	0.034	M
15.16	U	M	1.00	2.24	3.60	6	3.2	9.2	6.3	0.063	3
15.17	U	L	0.67	1.49	2.40	3	2.2	5.2	2.1	0.021	M
15.28	D	M	0.71	1.60	2.57	1.8	2.2	4	4.1	0.041	2
15.28	D	M	1.11	2.49	4.00	2.4	5.2	7.6	6.2	0.062	3
15.29	U	M	0.83	1.86	3.00	5.4	2.2	7.6	8	0.08	M
15.45	U	S	0.53	1.18	1.89	2.4	1.2	3.6	5.9	0.059	4
15.45	U	L	0.59	1.32	2.12	4.7	15	19.7	7.6	0.076	M
15.46	D	M	1.25	2.80	4.50	4.7	15	19.7	7.6	0.076	M
15.46	D	M	1.00	2.24	3.60	4.7	15	19.7	4.4	0.044	M
15.48	U	S	0.83	1.86	3.00	5.4	4.2	9.6	5.3	0.053	M
15.49	U	S	0.77	1.72	2.77	4.7	3.7	8.4	6.6	0.066	3
15.49	U	M	1.25	2.80	4.50	4.7	3.7	8.4	6.6	0.066	2
15.54	U	M	0.83	1.86	3.00	3.5	4.2	7.7	2.4	0.024	M
16.04	D	M	0.91	2.03	3.27	4.7	5.2	9.9	6.1	0.061	M
16.05	D	M	0.83	1.86	3.00	4.3	3.2	7.5	5.5	0.055	M
16.05	D	M	1.11	2.49	4.00	3.5	1.2	4.7	6.3	0.063	M
16.13	U	M	1.00	2.24	3.60	5.4	6.5	11.9	5.5	0.055	3
16.23	D	M	1.00	2.24	3.60	4.7	5.2	9.9	8.5	0.085	M
16.24	D	M	1.11	2.49	4.00	3.5	4.2	7.7	6.8	0.068	M
16.25	D	L	1.11	2.49	4.00	4.7	3.7	8.4	7	0.07	M
16.26	U	L	1.11	2.49	4.00	7.1	12.5	19.6	6.8	0.068	3
16.32	U	L	1.00	2.24	3.60	1.2	4.7	5.9	6.4	0.064	3
16.34	U	L	1.11	2.49	4.00	3.5	2.2	5.7	5.5	0.055	3
16.35	U	L	1.00	2.24	3.60	2.4	3.2	5.6	4.8	0.048	M
16.36	U	B	0.91	2.03	3.27	2.4	4.2	6.6	3.8	0.038	3
16.37	U	S	1.11	2.49	4.00	1.2	1.2	2.4	2.2	0.022	3
16.39	U	M	0.91	2.03	3.27	5.4	1.2	6.6	3.6	0.036	M
16.39	D	M	0.77	1.72	2.77	2.4	2.2	4.6	3.6	0.036	3
16.40	D	L	0.91	2.03	3.27	1.8	1.7	3.5	6.3	0.063	M
16.44	D	M	0.63	1.40	2.25	8.4	5.2	13.6	4.3	0.043	M
16.44	U	M	0.77	1.72	2.77	8.4	5.2	13.6	4.5	0.045	3

Site 2: Wallingford - Upstream of Wallingford Bridge

Monitored at a reeded bank on 8th August 1992 (average channel velocity = 3.3 cm/s)

Time	Direction U/D	Boat Type S/M/L/B	Boat Velocity (m/s)	Boat Velocity (mph)	Boat Velocity (km/hr)	Drawdown (cm)	Elevation (cm)	Wave Height (cm)	Max. Velocity (cm/s)	Max. Velocity (m/s)	Sailing position (1/2/3/4/M)
17.24	U	L	0.91	2.03	3.27	1.2	1.7	2.9	7.1	0.071	3
17.27	U	M	0.83	1.86	3.00	1.9	1.2	3.1	6.2	0.062	3
17.30	D	M	1.43	3.20	5.14	3.5	1.2	4.7	6.8	0.068	2
17.33	D	L	1.00	2.24	3.60	1.2	0	1.2	4.6	0.046	M
17.34	D	L	0.91	2.03	3.27	1.2	0	1.2	4.9	0.049	2
17.35	U	S	0.59	1.32	2.12	0.6	1.2	1.8	5.2	0.052	3
17.37	U	L	1.00	2.24	3.60	3.5	5.8	9.3	7.4	0.074	3
17.46	U	L	0.63	1.40	2.25	0.6	0.6	1.2	3.8	0.038	3
17.48	D	M	1.11	2.49	4.00	0.6	1.2	1.8	5.6	0.056	M
17.50	U	L	0.91	2.03	3.27	0.6	3.5	4.1	6.9	0.069	3
17.51	U	M	0.83	1.86	3.00	1.2	5.8	7	6.9	0.069	3
17.51	U	S	1.11	2.49	4.00	1.2	4.6	5.8	17.9	0.179	M
17.54	D	L	1.11	2.49	4.00	0	2.4	2.4	6.1	0.061	M
17.59	U	S	0.91	2.03	3.27	0.6	2.4	3	5.2	0.052	3
18.06	D	L	1.00	2.24	3.60	0	0.6	0.6	4	0.04	M
18.07	D	L	1.00	2.24	3.60	0.6	1.7	2.3	5.2	0.052	M
18.12	U	S	1.11	2.49	4.00	1.2	11.8	13	15.5	0.155	2
18.19	D	S	1.00	2.24	3.60	1.2	2.4	3.6	3.9	0.039	M
18.24	D	M	0.77	1.72	2.77	0.6	0	0.6	2.7	0.027	3
18.28	D	S	0.83	1.86	3.00	0.6	1.7	2.3	6	0.06	M
18.30	U	L	1.00	2.24	3.60	0	7.2	7.2	6.1	0.061	3
18.37	D	L	0.83	1.86	3.00	0.6	0	0.6	4.7	0.047	3
18.41	D	L	0.50	1.12	1.80	0.25	0.25	0.5	4	0.04	M
18.53	U	M	0.83	1.86	3.00	1.2	5.8	7	6.9	0.069	3
18.55	D	L	0.91	2.03	3.27	0.6	2.4	3	9.2	0.092	M

U = upstream
D = downstream

S = small
M = medium
L = large
B = barge

1, 2, 3 & 4 = channel quarters
M = middle

Site 3: Goring - Upstream of Goring Weir

Monitored at a Nicospan-protected bank on 9th August 1992 (average channel velocity = 2.5 cm/s)

Time	Direction U/D	Boat Type S/M/L/B	Boat Velocity (m/s)	Boat Velocity (mph)	Boat Velocity (km/hr)	Drawdown (cm)	Elevation (cm)	Wave Height (cm)	Max. Velocity (cm/s)	Max. Velocity (m/s)	Sailing position (1/2/3/4/M)
10.18	D	L	0.91	2.03	3.27	1.2	0.6	1.8	4.7	0.047	M
10.23	U	M	0.91	2.03	3.27	4.6	2.2	6.8	4.5	0.045	3
10.24	U	L	0.91	2.03	3.27	6	4.2	10.2	6.5	0.065	M
10.25	U	M	0.83	1.86	3.00	2	1.7	3.7	4	0.04	3
10.32	D	L	1.25	2.80	4.50	6	4.2	10.2	6.6	0.066	3
10.32	D	M	1.25	2.80	4.50	3.5	5.7	9.2	7	0.07	M
10.38	D	L	1.43	3.20	5.14	2.4	2.2	4.6	2.6	0.026	3
10.40	D	L	1.43	3.20	5.14	2	1.2	3.2	3.3	0.033	3
10.57	D	M	1.25	2.80	4.50	2.4	7	9.4	4.1	0.041	2
10.58	D	M	1.43	3.20	5.14	1.2	4.2	5.4	5	0.05	M
10.59	D	M	1.25	2.80	4.50	6	4.2	10.2	6.5	0.065	3
11.07	U	M	1.43	3.20	5.14	6	12.5	18.5	8.7	0.087	3
11.07	U	L	1.43	3.20	5.14	6	12.5	18.5	8.7	0.087	M
11.09	U	L	1.43	3.20	5.14	3	7.7	10.7	7.9	0.079	M
11.10	D	M	1.43	3.20	5.14	2.4	6.5	8.9	6	0.06	M
11.11	D	M	1.43	3.20	5.14	1.8	4.7	6.5	5.6	0.056	M
11.18	D	M	1.25	2.80	4.50	3	4.7	7.7	5	0.05	M
11.21	U	S	1.43	3.20	5.14	5.4	10	15.4	8.8	0.088	3
11.25	U	L	1.11	2.49	4.00	4.6	5.7	10.3	4.3	0.043	3
11.33	D	M	1.11	2.49	4.00	4.6	7	11.6	4.1	0.041	M
11.34	D	M	1.25	2.80	4.50	1.2	5.7	6.9	5.5	0.055	M
11.35	D	L	1.00	2.24	3.60	1.2	3.2	4.4	4.6	0.046	3
11.36	D	L	1.11	2.49	4.00	0	5.2	5.2	6	0.06	3
11.37	D	L	1.11	2.49	4.00	1.2	4.2	5.4	4.6	0.046	3
11.42	U	M	1.25	2.80	4.50	4.3	8.7	13	6.4	0.064	3
11.44	U	M	1.25	2.80	4.50	1.2	5.2	6.4	4.5	0.045	3
11.46	D	M	1.43	3.20	5.14	3.5	13	16.5	7.5	0.075	2
11.47	D	B	1.25	2.80	4.50	4.6	5.2	9.8	7.3	0.073	2
11.47	D	B	1.11	2.49	4.00	6	5.2	11.2	8.6	0.086	2
11.48	D	M	1.25	2.80	4.50	3	3.7	6.7	8.2	0.082	M
11.51	U	M	1.25	2.80	4.50	4.6	5.2	9.8	7.5	0.075	3
12.01	U	L	1.11	2.49	4.00	3	8.7	11.7	3.5	0.035	3
12.02	D	M	1.25	2.80	4.50	6.5	10	16.5	7.2	0.072	M
12.03	U	M	1.00	2.24	3.60	2.4	5.2	7.6	4.3	0.043	3
12.04	U	B	1.11	2.49	4.00	1.2	4.2	5.4	5.9	0.059	3
12.05	D	B	1.11	2.49	4.00	0.6	2.2	2.8	5.2	0.052	M
12.09	D	L	1.11	2.49	4.00	0	2.7	2.7	3.5	0.035	2
12.11	D	B	1.11	2.49	4.00	0.6	2.2	2.8	4.8	0.048	M
12.13	U	L	1.43	3.20	5.14	2.4	7.7	10.1	7.8	0.078	3
12.15	U	L	1.67	3.73	6.00	4.6	10	14.6	6.3	0.063	M
12.18	U	M	1.43	3.20	5.14	1.2	6.5	7.7	6.7	0.067	3
12.23	U	M	1.43	3.20	5.14	2.4	5.2	7.6	4.3	0.043	3
12.24	U	M	1.43	3.20	5.14	7.2	10	17.2	6.4	0.064	3
12.24	D	M	1.43	3.20	5.14	4.6	10	14.6	6.4	0.064	M
12.25	D	B	0.83	1.86	3.00	2.4	11.2	13.6	7.1	0.071	3
12.25	U	M	1.43	3.20	5.14	2.4	11.2	13.6	10.1	0.101	M
12.27	U	L	1.43	3.20	5.14	3	11.2	14.2	7.9	0.079	3
12.28	U	M	1.11	2.49	4.00	2.4	3.2	5.6	7.1	0.071	3
12.41	D	M	1.43	3.20	5.14	3	6.5	9.5	4.9	0.049	2
12.42	D	L	1.00	2.24	3.60	1.2	3.2	4.4	4.5	0.045	3
12.42	D	M	1.25	2.80	4.50	1.2	3.2	4.4	5.1	0.051	2
12.43	D	M	0.71	1.60	2.57	0	4.2	4.2	7.4	0.074	M

Frequency distribution tables for boat velocities and wave heights recorded at the wood piled, reeded and Nicospan protected banks.

Frequency distribution table for boats passing the wood piled bank

Time period	Boat velocity categories (mph)					Wave height category (cm)					Maximum near-bank velocity category (cm/s)					Direction of passage		Total number of boats
	0-1	1-2	2-3	3-4	>4	0-5	5-10	10-15	15-20	>20	2-4	4-6	6-8	8-10	>10	Upstream	Downstream	
10:00-11:00	0	5	6	0	0	3	6	2	0	0	M	M	M	M	M	6	5	11
11:00-12:00	1	6	5	0	0	2	2	7	1	0	M	M	M	M	M	5	7	12
12:00-13:00	0	2	8	4	0	1	2	8	2	1	M	M	M	M	M	9	5	14
13:00-14:00	0	4	5	0	0	3	4	1	1	0	1	3	0	0	0	5	4	9
14:00-15:00	0	5	3	0	0	2	3	3	0	0	3	3	1	1	0	4	4	8
15:00-16:00	0	11	8	0	1	3	12	1	3	1	4	9	7	0	0	13	7	20
16:00-17:00	0	4	14	0	0	4	10	3	1	0	4	6	7	1	0	9	9	18
	1	37	49	4	1	18	39	25	8	2	12	27	15	2	0	51	41	92

NB: M = missing data

Frequency distribution table for boats passing the reeded bank

Time period	Boat velocity categories (mph)					Wave height category (cm)					Maximum near-bank velocity category (cm/s)					Direction of passage		Total number of boats
	0-1	1-2	2-3	3-4	>4	0-5	5-10	10-15	15-20	>20	2-4	4-6	6-8	8-10	>10	Upstream	Downstream	
17:00-18:00	0	4	9	1	0	11	3	0	0	0	1	5	7	0	1	9	5	14
18:00-19:00	0	5	6	0	0	8	2	1	0	0	4	3	2	1	1	3	8	11
	0	9	15	1	0	19	5	1	0	0	5	8	9	1	2	12	13	25

Frequency distribution table for boats passing the Nicospan protected bank

Time period	Boat velocity categories (mph)					Wave height category (cm)					Maximum near-bank velocity category (cm/s)					Direction of passage		Total number of boats
	0-1	1-2	2-3	3-4	>4	0-5	5-10	10-15	15-20	>20	2-4	4-6	6-8	8-10	>10	Upstream	Downstream	
10:00-11:00	0	1	7	3	0	4	4	3	0	0	3	4	4	0	0	3	8	11
11:00-12:00	0	0	13	7	0	1	10	5	4	0	0	10	5	5	0	8	12	20
12:00-13:00	0	2	10	9	0	6	6	7	2	0	2	8	10	0	1	11	10	21
	0	3	30	19	0	11	20	15	6	0	5	22	19	5	1	22	30	52

Appendix 5.4 Factors influencing erosion at 147 sites

INDICATORS OF BANK EROSION ALONG THE RIVER THAMES

Erosion site no.	Vol. III Map No.	Reach	Bank location: left or right (LB/RB)	Length of erosion at protected and unprotected banks (m): Protected: Sheet piling	Concrete/masonry	Concrete bagwork	Brickwork	Spiling	Gabions	Nicospan	Unprotected: Bare earth	Grass	Shrubs	Sparse trees	Wooded	Total length of bank erosion (m)	Erosion category	Erosion Group A: Channel planform and geometry: u/s of weir	d/s of weir	inside of bend	outside of bend	sinuosity	tributary channel	opposite island	opposite sheet piling	u/s of bridge	d/s of bridge	Erosion Group B: Land & bank use: public access	fishing	livestock grazing	cattle access	Erosion Group C: Navigation: u/s of lock	d/s of lock	near lock	ferry site	boat yard	moorings	boat wash	spending beach
1	1	Buscot	LB	0	0	0	0	0	0	0	150	0	300	50	0	500	A-B-C					X								X								X	
2	1	Buscot	RB	0	0	0	0	0	0	0	0	0	200	0	0	200	A-B-C					X								X								X	
3	1	Buscot	RB	0	0	0	0	0	0	0	20	0	30	0	0	50	A-B				X									X	X								
4	2	Grafton	LB	0	0	0	0	0	0	0	40	0	10	0	0	50	C															X					X	X	
5	2	Grafton	LB	0	0	0	0	0	0	0	200	0	300	0	0	500	A-C			X		X																X	
6	2	Grafton	RB	0	0	0	0	0	0	0	250	0	0	0	0	250	A-C					X																X	
7	2	Grafton	RB	0	0	0	0	0	0	0	350	20	280	0	0	650	A-C					X															X		
8	2	Grafton	LB	0	0	0	0	0	0	0	500	0	150	0	0	650	A-C					X															X		
9	2	Grafton	RB	0	0	0	0	0	0	0	50	50	0	300	0	400	B-C													X		X			X		X	X	
10	2	Grafton	RB	0	0	0	0	0	0	0	200	240	60	0	0	500	B-C													X	X	X					X	X	
11	2	Grafton	LB	0	0	0	0	0	0	0	150	150	50	0	0	350	C															X						X	
12	3	Radcot	LB	0	0	0	0	0	0	0	40	0	230	30	50	350	A-C				X	X											X					X	
13	3	Radcot	LB	0	0	0	0	0	0	0	80	0	120	0	0	200	A-C					X																X	
14	3	Radcot	RB	0	0	0	0	0	0	0	0	0	50	0	0	50	A-B					X								X									
15	3	Radcot	LB	0	0	0	0	0	0	0	50	40	110	0	0	200	C																					X	
16	3	Radcot	RB	0	0	0	0	0	0	0	50	50	100	0	0	200	A-C										X										X		
17	3	Radcot	RB	0	0	0	0	0	0	0	250	0	0	0	0	250	A-C			X												X					X		
18	4	Rushey	RB	0	0	0	0	0	0	0	650	100	250	0	0	1000	A-B-C					X							X									X	
19	4	Rushey	LB	0	0	0	0	0	0	0	650	400	0	50	0	1100	A-B-C					X							X									X	
20	5	Shifford	RB	0	0	0	0	0	0	0	170	0	60	70	0	300	A-C					X											X					X	
21	5	Shifford	RB	0	0	0	0	0	0	0	100	0	0	0	0	100	A-C				X	X															X	X	
22	5	Shifford	RB	0	0	0	0	0	0	0	100	0	0	0	0	100	A				X																		
23	5	Shifford	LB	0	0	0	0	0	0	0	330	70	0	0	0	400	A-B				X									X	X								
24	5	Shifford	RB	0	0	0	0	0	0	0	250	0	0	0	0	250	A-C					X																X	
25	5	Shifford	RB	0	0	0	0	0	0	0	180	0	70	0	0	250	A-C			X																		X	
26	5	Shifford	RB	0	0	0	0	0	0	0	20	0	0	0	130	150	C															X						X	
27	6	Northmoor	LB	0	0	0	0	0	0	0	100	0	0	0	0	100	A-B				X		X							X									
28	6	Northmoor	RB	0	0	0	0	0	0	0	20	170	310	0	0	500	A-C									X											X	X	
29	6	Northmoor	RB	0	0	0	0	0	0	0	20	40	70	470	0	600	B-C													X		X					X	X	
30	7	Pinkhill	LB	0	0	0	0	0	0	0	60	0	40	0	0	100	B-C													X	X						X	X	
31	7	Pinkhill	LB	0	0	0	0	0	0	0	0	0	0	250	0	250	A-B					X							X										
32	7	Pinkhill	RB	0	0	0	0	0	0	0	70	0	100	20	0	190	B													X	X								
33	7	Pinkhill	LB	0	0	0	0	0	0	0	140	80	0	80	0	300	A-B					X								X									
34	8	Eynsham	LB	0	0	0	0	0	0	0	60	0	340	0	0	400	A-C					X															X	X	
35	8	Eynsham	RB	0	0	0	0	0	0	0	20	0	130	0	0	150	A-B-C					X							X	X	X						X	X	
36	9	Kings	RB	0	0	0	0	0	0	0	60	0	20	0	20	100	B-C												X	X	X			X					
37	9	Kings	LB	0	0	0	0	0	0	0	120	0	240	90	0	450	B													X	X								
38	9	Kings	RB	0	0	0	0	0	0	0	80	180	40	0	0	300	B-C													X	X			X				X	
39	9	Kings	LB	0	0	0	0	0	0	0	50	0	0	0	0	50	A-C				X																	X	
40	10	Godstow	RB	0	0	110	0	220	0	0	160	50	30	30	0	600	B-C													X	X			X				X	X

Appendix 5.4 continued

INDICATORS OF BANK EROSION ALONG THE RIVER THAMES

Length of erosion at protected and unprotected banks (m)

Erosion site no.	Vol. III Map No.	Reach	Bank location: left or right (LB/RB)	Protected: Sheet piling	Protected: Concrete/masonry	Protected: Concrete bagwork	Protected: Brickwork	Protected: Spiling	Protected: Gabions	Protected: Nicospan	Unprotected: Bare earth	Unprotected: Grass	Unprotected: Shrubs	Unprotected: Sparse trees	Unprotected: Wooded	Total length of bank erosion (m)	Erosion category
41	11	Osney	LB	0	0	0	0	0	0	0	120	0	0	0	0	120	A-C
42	11	Osney	RB	0	0	0	0	0	0	0	120	40	0	80	0	240	B-C
43	11	Osney	LB	0	0	0	0	0	0	0	150	50	0	0	0	200	B-C
44	11	Osney	LB	0	0	100	0	0	0	0	0	0	0	0	0	100	C
45	11	Osney	LB	0	100	100	50	0	0	0	0	0	0	0	0	250	C
46	12	Iffley	RB	0	0	200	0	0	0	0	0	100	0	0	0	300	B-C
47	12	Iffley	RB	0	0	50	120	0	0	0	0	80	0	0	0	250	C
48	12	Iffley	LB	0	0	0	0	0	0	0	30	50	0	170	0	250	B-C
49	13	Sandford	RB	0	0	0	0	0	0	0	60	20	0	20	0	100	C
50	13	Sandford	RB	0	0	0	0	0	0	0	60	250	0	40	0	350	B-C
51	14	Abingdon	LB	0	0	0	0	0	0	0	100	0	0	50	0	150	B-C
52	14	Abingdon	LB	0	0	0	0	0	0	0	60	0	0	60	0	120	B-C
53	14	Abingdon	LB	0	0	0	0	0	0	0	20	0	0	0	0	20	B-C
54	14	Abingdon	LB	0	0	100	0	0	0	0	0	0	0	0	0	100	C
55	15	Culham	LB	0	0	0	0	0	0	0	150	80	0	0	0	230	C
56	15	Culham	RB	0	200	0	0	0	0	0	0	0	0	0	0	200	C
57	15	Culham	LB	0	0	100	0	0	0	0	100	0	0	0	0	200	A-C
58	15	Culham	LB	0	0	0	0	0	0	0	20	100	250	0	0	370	A-B-C
59	16	Clifton	LB	0	0	150	0	0	0	0	0	0	0	0	0	150	C
60	16	Clifton	RB	0	0	0	0	0	0	0	250	0	0	0	0	250	B
61	16	Clifton	RB	0	0	0	0	0	0	0	180	300	0	350	0	830	B
62	17	Days	RB	0	0	0	0	0	0	0	900	0	0	0	0	900	B-C
63	17	Days	LB	0	0	0	0	0	0	0	250	50	0	250	0	550	C
64	18	Benson	LB	0	0	0	0	0	0	0	190	0	200	0	0	390	A-B-C
65	18	Benson	RB	0	0	0	0	0	0	0	350	0	0	0	0	350	A-C
66	18	Benson	RB	0	0	0	0	0	0	0	160	40	100	0	0	300	A-C
67	19	Cleeve	LB	0	0	0	0	0	0	0	20	0	0	0	0	20	B
68	19	Cleeve	LB	0	0	0	0	0	0	0	200	0	0	0	0	200	A-B-C
69	19	Cleeve	LB	0	0	0	0	0	0	0	20	80	60	40	0	200	B-C
70	19	Cleeve	RB	0	0	0	0	0	0	0	1070	250	0	0	0	1320	B-C
71	20	Goring	RB	0	0	0	0	0	0	0	0	50	0	0	0	50	B-C
72	21	Whitchurch	LB	0	0	0	0	0	0	0	120	0	100	0	0	220	A-B-C
73	21	Whitchurch	RB	0	0	0	0	0	0	0	20	620	0	0	60	700	B-C
74	21	Whitchurch	RB	0	0	0	0	0	0	0	0	600	0	0	0	600	B-C
75	21	Whitchurch	RB	50	0	0	0	0	0	0	60	740	0	0	0	850	B-C
76	22	Mapledurham	RB	0	0	0	0	0	0	0	350	100	0	50	0	500	C
77	22	Mapledurham	RB	0	0	50	0	0	0	0	250	1020	0	230	0	1550	A-B-C

Erosion site no.	Erosion Group A: Channel planform and geometry: u/s of weir	d/s of weir	inside of bend	outside of bend	sinuosity	tributary channel	opposite island	opposite sheet piling	u/s of bridge	d/s of bridge	Erosion Group B: Land & bank use: public access	fishing	livestock grazing	cattle access	Erosion Group C: Navigation: u/s of lock	d/s of lock	near lock	ferry site	boat yard	moorings	boat wash	expanding beach
41		X	X													X					X	X
42												X	X	X			X				X	X
43												X	X	X			X				X	X
44																					X	
45															X						X	
46												X									X	
47															X		X				X	
48													X		X							X
49																X				X	X	
50												X	X	X						X	X	
51												X				X					X	
52												X					X				X	
53													X	X								
54															X					X	X	
55																				X	X	
56																					X	
57			X																	X	X	X
58				X									X									X
59															X		X				X	
60												X	X	X								
61												X	X	X								
62													X							X	X	
63															X					X	X	
64					X								X	X						X	X	
65					X																X	
66				X																X		
67														X								
68										X	X	X								X	X	X
69													X	X						X	X	
70											X		X				X			X	X	X
71											X										X	
72			X								X											X
73													X	X							X	
74												X									X	
75												X								X	X	
76																X				X		
77			X								X		X	X							X	X

Appendix 5.4 continued

Length of erosion at protected and unprotected banks (m)

Erosion site no.	Vol. III Map No.	Reach	Bank location: left or right (LB/RB)	Protected: Sheet piling	Protected: Concrete/masonry	Protected: Concrete bagwork	Protected: Brickwork	Protected: Spiling	Protected: Gabions	Protected: Nicospan	Unprotected: Bare earth	Unprotected: Grass	Unprotected: Shrubs	Unprotected: Sparse trees	Unprotected: Wooded	Total length of bank erosion (m)	Erosion category
78	23	Caversham	RB	0	0	0	0	0	0	0	40	80	40	40	0	200	A-B-C
79	23	Caversham	RB	100	0	0	0	0	0	0	0	0	0	0	0	100	A
80	23	Caversham	LB	30	0	0	0	0	0	0	0	0	170	0	0	200	A-C
81	23	Caversham	RB	100	0	0	0	0	0	0	0	0	0	0	0	100	A-B-C
82	23	Caversham	RB	50	0	0	0	0	0	0	0	0	0	0	0	50	A-B-C
83	24	Sonning	RB	0	0	0	0	0	0	0	50	0	60	40	0	150	A-B-C
84	24	Sonning	RB	0	0	0	0	0	0	0	120	0	0	0	0	120	B
85	24	Sonning	LB	0	0	0	0	0	0	0	20	0	30	0	0	50	A-C
86	24	Sonning	RB	0	0	50	0	0	0	0	0	0	0	0	0	50	C
87	25	Shiplake	RB	0	30	0	0	0	0	0	20	0	0	0	0	50	A-B
88	25	Shiplake	LB	0	0	0	0	0	0	0	80	0	0	80	0	160	A-C
89	25	Shiplake	RB	0	0	0	0	0	0	0	0	0	0	0	200	200	A-B-C
90	25	Shiplake	LB	0	0	0	0	0	0	0	50	0	0	0	0	50	A-C
91	25	Shiplake	RB	0	0	0	0	0	0	0	140	40	440	30	0	650	B-C
92	25	Shiplake	RB	0	0	0	0	0	0	0	40	160	0	0	0	200	A-B-C
93	25	Shiplake	LB	0	0	0	0	0	0	0	100	100	20	0	0	220	B-C
94	26	Marsh	LB	0	0	0	0	0	0	0	100	0	180	70	0	350	A-C
95	26	Marsh	LB	0	0	0	0	0	0	0	100	0	0	0	0	100	A-C
96	26	Marsh	LB	40	0	0	0	0	0	0	110	0	160	0	0	310	B-C
97	27	Hambledon	RB	0	60	20	0	0	0	0	0	0	0	0	0	80	C
98	27	Hambledon	LB	140	0	10	0	0	0	0	0	0	0	0	0	150	C
99	27	Hambledon	RB	60	0	0	0	0	0	0	0	0	0	0	0	60	A-C
100	27	Hambledon	LB	0	0	0	0	0	0	0	240	100	0	160	0	500	C
101	27	Hambledon	LB	0	0	0	0	0	0	0	20	0	30	0	0	50	C
102	27	Hambledon	RB	0	0	0	0	0	0	0	100	100	0	0	0	200	A-C
103	28	Hurley	LB	0	0	0	0	0	0	0	50	100	0	0	0	150	B
104	28	Hurley	LB	0	0	0	0	0	0	0	180	40	0	20	60	300	A-C
105	28	Hurley	RB	0	0	0	0	0	0	0	80	350	200	0	0	630	A-B-C
106	28	Hurley	RB	0	0	70	0	0	0	0	50	50	0	0	0	170	C
107	29	Temple	RB	0	0	100	0	0	0	0	0	0	0	0	0	100	B-C
108	30	Marlow	LB	0	0	40	0	0	0	70	40	0	30	0	0	180	B-C
109	31	Cookham	RB	0	0	0	0	0	0	0	30	0	0	0	0	30	C
110	31	Cookham	LB	0	0	0	0	0	0	0	100	130	0	20	0	250	A-B-C
111	31	Cookham	LB	0	0	0	0	0	0	0	150	50	0	350	0	550	A-B-C
112	31	Cookham	RB	0	0	0	0	0	0	0	380	0	0	20	0	400	A-C
113	31	Cookham	LB	0	150	0	0	0	0	0	0	0	0	0	0	150	C

INDICATORS OF BANK EROSION ALONG THE RIVER THAMES

Erosion site no.	Erosion Group A: Channel planform and geometry: u/s of weir	d/s of weir	inside of bend	outside of bend	sinuosity	tributary channel	opposite island	opposite sheet piling	u/s of bridge	d/s of bridge	Erosion Group B: Land & bank use: public access	fishing	livestock grazing	cattle access	Erosion Group C: Navigation: u/s of lock	d/s of lock	near lock	ferry site	boat yard	moorings	boat wash	spending beach
78		X										X				X						X
79				X																		
80			X																		X	
81									X		X	X								X	X	
82							X				X	X									X	
83		X	X									X					X				X	X
84												X										
85			X																			X
86															X					X	X	
87										X	X											
88			X		X																X	
89			X		X							X									X	
90			X		X																	X
91													X									X
92			X										X								X	X
93													X	X	X						X	
94			X							X							X	X			X	X
95			X																		X	
96												X								X	X	X
97																					X	
98																				X	X	
99			X																		X	
100																				X		
101																						X
102			X												X					X	X	
103													X	X								
104			X																	X	X	X
105			X									X								X	X	X
106															X						X	
107											X	X									X	
108											X	X									X	
109																				X	X	X
110							X					X										X
111								X				X										X
112				X																X		X
113																					X	

Appendix 5.4 continued

Length of erosion at protected and unprotected banks (m)

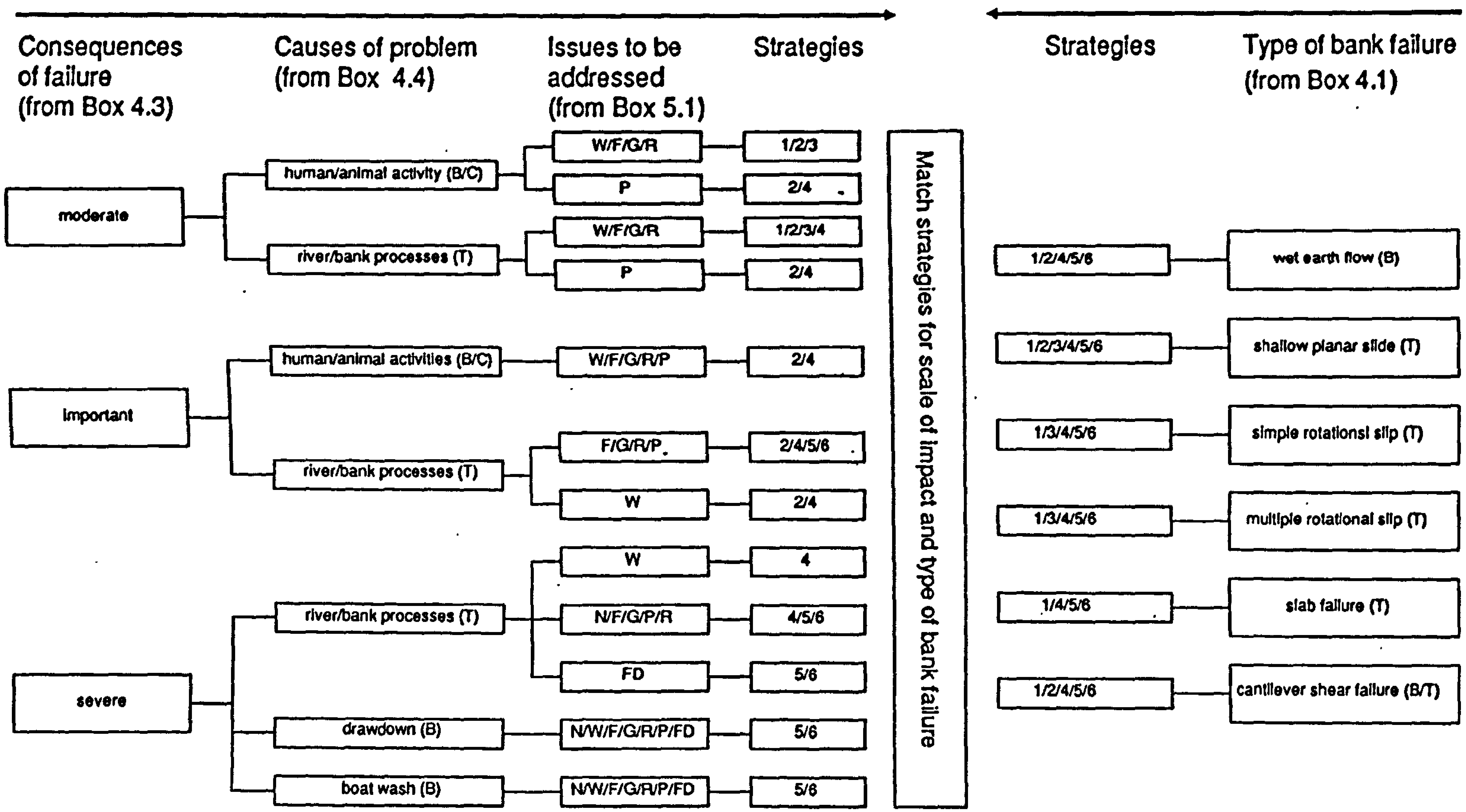
Erosion site no.	Vol. III Map No.	Reach	Bank location: left or right (LB/RB)	Protected: Sheet piling	Protected: Concrete/masonry	Protected: Concrete bagwork	Protected: Brickwork	Protected: Spiling	Protected: Gabions	Protected: Nicospan	Unprotected: Bare earth	Unprotected: Grass	Unprotected: Shrubs	Unprotected: Sparse trees	Unprotected: Wooded	Total length of bank erosion (m)	Erosion category
114	32	Boulters	LB	0	0	0	0	0	0	0	80	0	0	0	70	150	A-C
115	32	Boulters	RB	50	0	0	0	0	0	0	0	0	0	0	0	50	C
116	33	Bray	LB	0	0	0	0	0	0	0	20	0	0	0	0	20	B-C
117	34	Boveney	RB	0	0	0	0	0	0	0	40	0	0	0	30	70	B
118	34	Boveney	LB	0	0	0	0	0	0	0	50	0	0	30	0	80	A-C
119	34	Boveney	LB	0	50	0	0	0	0	0	50	0	0	0	0	100	A-B-C
120	34	Boveney	LB	0	0	0	0	0	0	0	50	0	0	50	0	100	C
121	35	Romney	LB	0	200	0	0	0	0	0	100	50	0	0	0	350	A-B-C
122	35	Romney	LB	0	0	140	0	0	0	0	60	50	20	0	0	270	B-C
123	35	Romney	LB	0	0	100	0	0	0	0	0	0	0	0	0	100	C
124	35	Romney	RB	50	0	150	0	0	0	0	0	0	0	0	0	200	B-C
125	35	Romney	LB	0	0	0	0	0	0	0	180	50	0	0	0	230	A-B-C
126	36	Old Windsor	RB	0	0	70	0	0	0	0	100	0	0	100	0	270	A-B-C
127	36	Old Windsor	RB	0	0	100	0	0	0	0	0	0	0	0	0	100	A-B-C
128	37	Egham	RB	0	0	50	0	0	0	0	0	0	0	0	0	50	A-B-C
129	37	Egham	RB	0	0	0	0	0	0	0	30	0	0	0	0	30	A-B-C
130	38	Penton Hook	RB	0	0	20	0	0	0	0	20	10	0	0	0	50	A-B-C
131	38	Penton Hook	RB	20	60	20	0	0	0	0	0	0	0	0	0	100	B-C
132	39	Chertsey	LB	0	0	220	0	0	0	0	60	100	0	20	0	400	A-B-C
133	40	Shepperton	LB	0	0	50	0	0	0	0	100	100	0	0	0	250	A-B-C
134	40	Shepperton	RB	0	0	0	0	0	0	0	20	0	30	0	0	50	A-B-C
135	40	Shepperton	LB	0	0	100	0	0	0	0	80	0	0	20	0	200	A-C
136	40	Shepperton	LB	0	0	60	0	0	0	0	40	0	20	0	0	120	B-C
137	41	Sunbury	RB	0	20	100	0	0	0	0	0	0	0	0	0	120	B-C
138	41	Sunbury	LB(Is.)	0	0	50	0	0	0	0	0	0	0	0	0	50	C
139	41	Sunbury	RB	0	0	30	0	0	0	0	0	0	0	0	0	30	C
140	42	Molesey	LB	0	0	0	0	0	0	0	20	30	0	0	0	50	C
141	42	Molesey	RB	0	0	0	0	0	0	0	40	0	0	0	0	40	A-B-C
142	42	Molesey	RB	0	0	0	0	0	0	0	60	0	0	0	0	60	A-B-C
143	42	Molesey	RB	0	0	30	0	0	0	0	0	0	0	0	0	30	C
144	43	Teddington	LB	0	0	0	0	0	0	0	20	0	0	0	0	20	A-B-C
145	43	Teddington	LB	0	20	20	0	0	0	0	0	0	0	0	0	40	A-C
146	43	Teddington	LB	0	0	250	0	0	0	0	0	0	0	0	0	250	B-C
147	43	Teddington	RB	0	0	1000	0	0	0	0	0	0	0	0	0	1000	A-B-C

INDICATORS OF BANK EROSION ALONG THE RIVER THAMES

Erosion site no.	Erosion Group A: Channel planform and geometry: u/s of weir	d/s of weir	inside of bend	outside of bend	sinuosity	tributary channel	opposite island	opposite sheet piling	u/s of bridge	d/s of bridge	Erosion Group B: Land & bank use: public access	fishing	livestock grazing	cattle access	Erosion Group C: Navigation: u/s of lock	d/s of lock	near lock	ferry site	boat yard	moorings	boat wash	spending beach
114		X														X						
115																					X	
116											X					X					X	X
117												X										
118							X														X	
119			X								X										X	
120															X					X	X	
121				X								X								X	X	
122												X								X	X	
123																					X	
124												X								X	X	
125			X								X							X		X	X	
126			X									X									X	X
127				X								X					X				X	
128				X								X				X						
129			X								X											X
130									X			X				X						X
131												X								X	X	
132					X						X	X					X				X	X
133			X									X	X	X			X		X		X	X
134				X							X	X									X	X
135			X	X																X	X	X
136												X										X
137												X									X	X
138															X				X		X	
139															X				X		X	
140																X			X		X	X
141					X							X								X	X	
142			X									X								X	X	X
143															X					X	X	
144										X	X						X					X
145			X															X			X	
146												X								X	X	
147					X							X								X	X	

APPENDIX 6

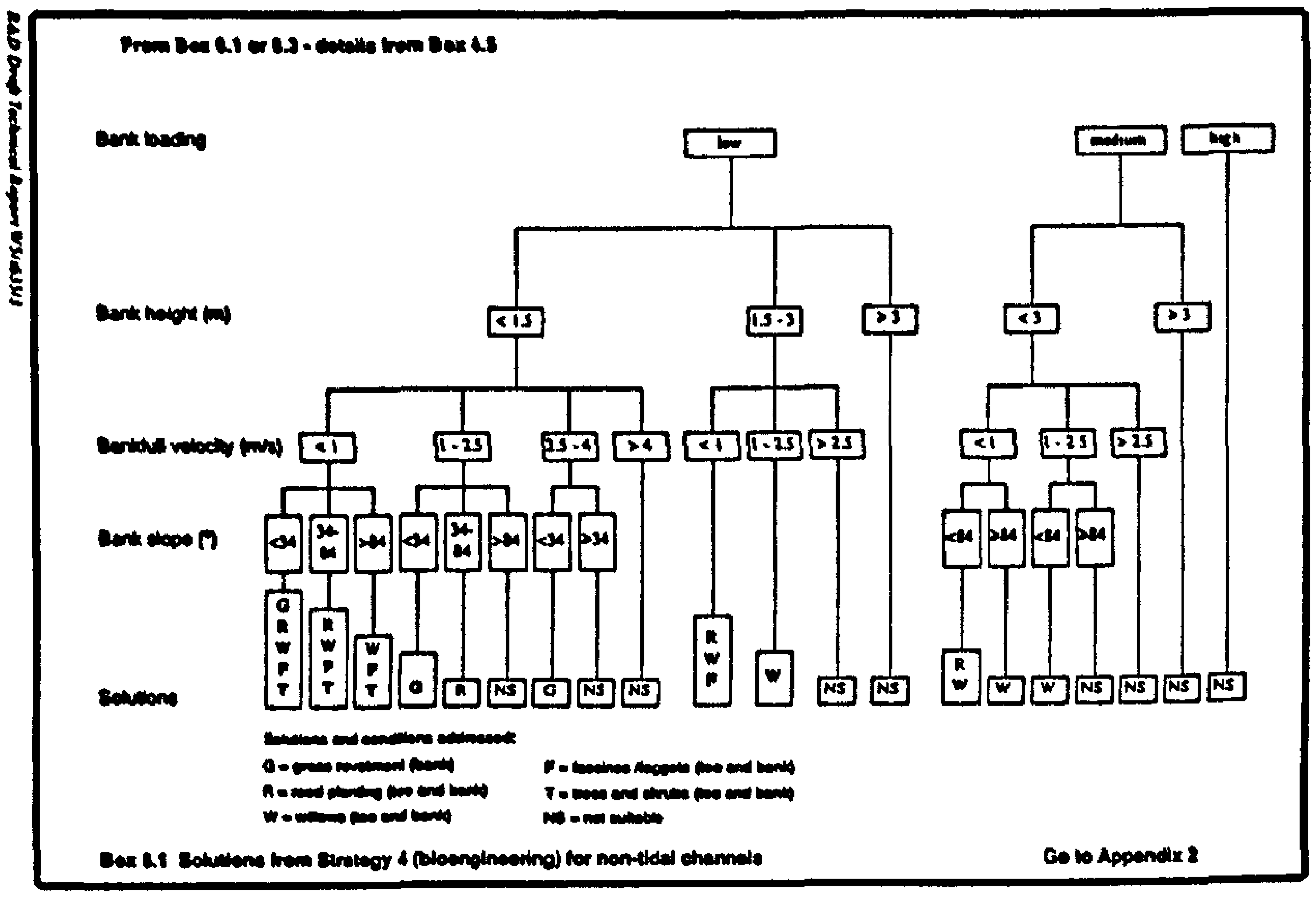
Appendix 6.1 Decision tree for selection of erosion control strategy (reproduced with permission from the Environment Agency)



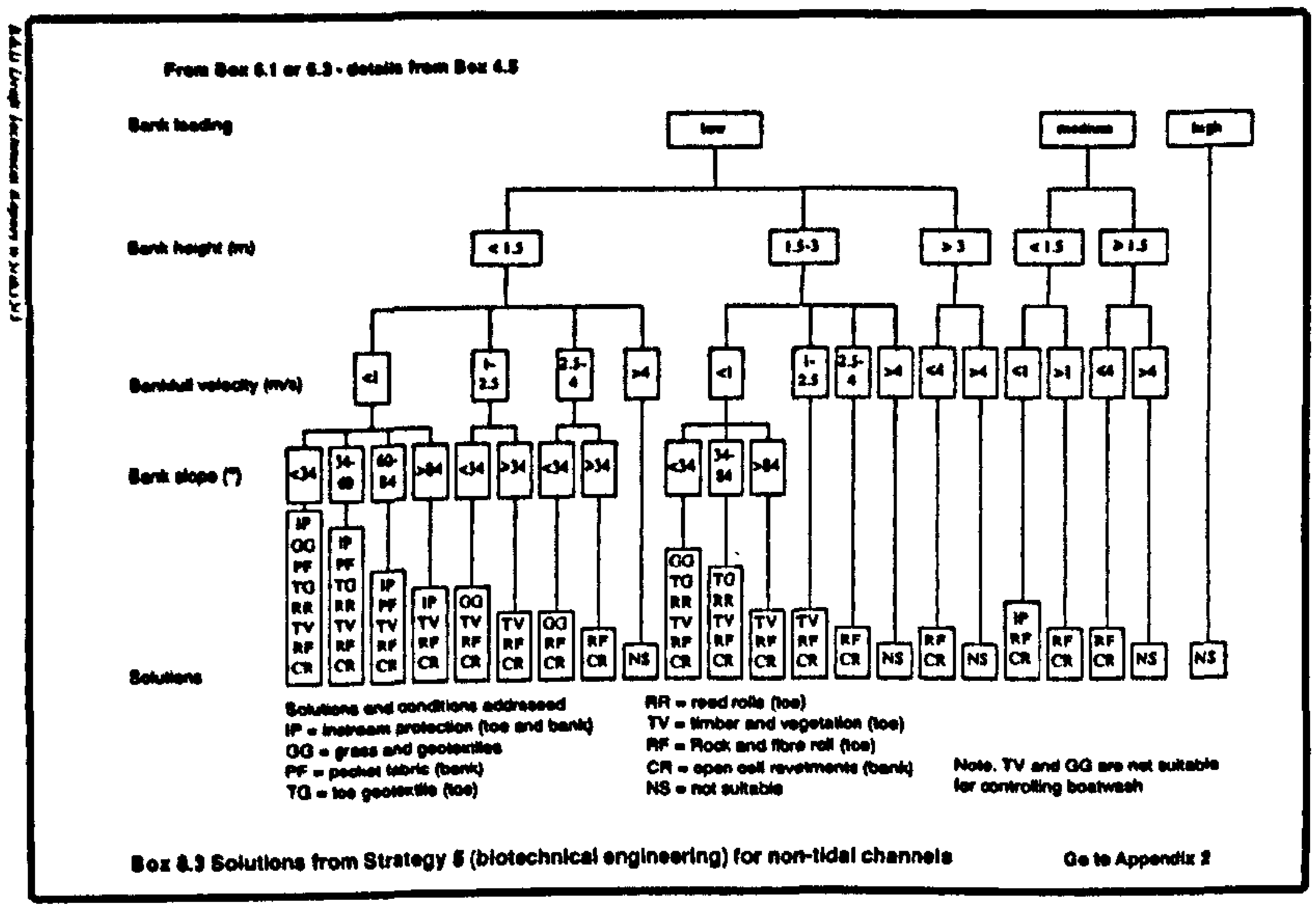
Box 6.1 Selection of strategies for non-tidal river channels

For Strategies 1, 2 and 3, go to Appendix 1 and Box 9.1 ➪
For Strategy 4, go to Box 8.1 or 8.2 ➪
For Strategy 5, go to Box 8.3 or 8.4 ➪
For Strategy 6, go to Box 8.5 ➪

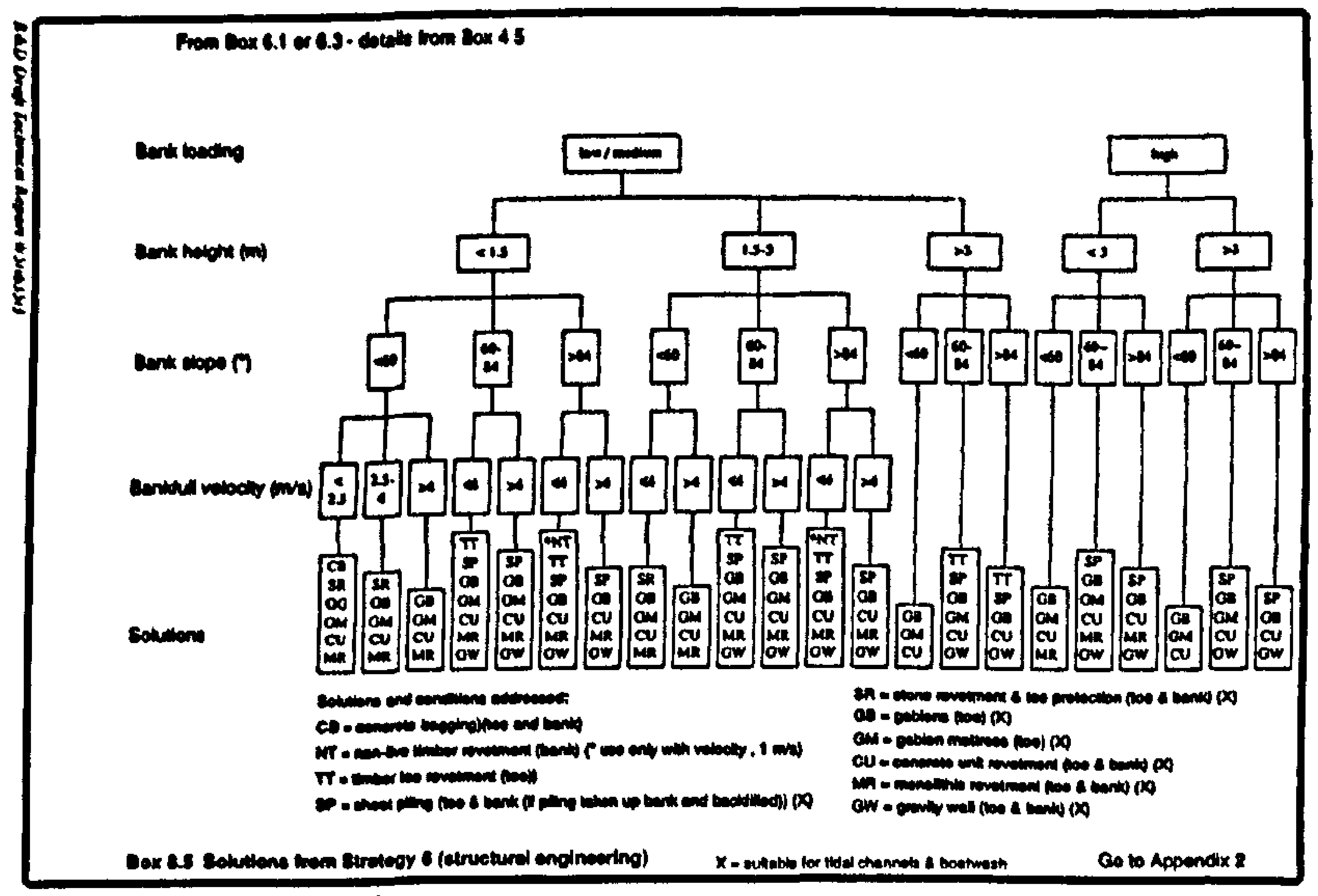
Appendix 6.2 Decision trees for selection of erosion control techniques (reproduced with permission from the Environment Agency)



Box 6.1 Solutions from Strategy 4 (bioengineering) for non-tidal channels



Box 6.3 Solutions from Strategy 5 (biotechnical engineering) for non-tidal channels



Box 6.5 Solutions from Strategy 6 (structural engineering)

Appendix 6.3

List of erosion control techniques on non-River Thames sites reviewed by the author during Phase II of NRA's R&D project (from NRA, 1994b).

Sites on the River Medway:

- Willow spiling at Teston
- Willow spiling upstream of Hartlake Bridge
- Willow spiling and reed planting downstream of Hartlake Bridge
- Willow spiling and reed planting at Yalding footbridge
  Willow spiling with a non woven geotextile and woven geotextile bags upstream of Hartlake Bridge
- Gabion baskets with a non woven geotextile and reed planting upstream of Hartlake Bridge
- Vertical timber revetment with a non woven geotextile and willow spiling with reed planting upstream of Yalding Bridge
- Riprap downstream of Porter's Sluice

Sites on the Ten Mile River, East Anglia :

- Woven pocketed geotextile with reed and sedge planting opposite Whitehall Pumping Station
- Non woven geotextile with reed planting upstream of Whitehall pumping Station
- Woven pocketed geotextile with reed planting upstream of Black Horse Farm on the Ten Mile River

Sites on the Broadland Rivers:

- Fascine mattresses and a geotextile with reed planting downstream of Lyon Dyke on the River Thurne
- Non woven geotextile with sedge planting at Chapelfield Marsh, River Ant
- Non woven geotextiles with reed planting adjacent to Thurne Mouth on the River Thurne
- Non woven geotextile and piling with reed and grass planting at Thurne Mouth on the River Bure
- Three dimensional plastic grid with reed planting upstream of Upton Mill on the River Bure
- Rubber tyre vertical revetment with reed planting near South Walsham Pump on the River Bure
- Wire mesh mattresses opposite South Walsham Pump on the River Bure
- Wire mesh mattresses at Mautby on the River Bure
- Open cell concrete blocks and geotextile at North Breydon, River Yare
- Open cell concrete with a geotextile at Bure Loop on the River Bure
- Vertical steel revetment with reed planting upstream of Upton Mill on the River Bure

Appendix 6.4 Details of erosion control case studies

Case study	Reach	Strategy adopted	Technique used	Cattle	Footpath	Fishing	Recreation	Lock cut	Near lock	Weir stream	Side sluice	Impinging flow	Outside of bend	Near hard engineering	Inside of bend	Standing beach	Failure mechanism	Major causes of erosion	Consequences of erosion	Issues to be addressed	Recommended strategies 1	2	3	4	5	6
1	Godstow	5 : biotechnical engineering	geotextile + spiling	X	X													animal activity	moderate	R : public path*	**1**	2	**3**			
2	Godstow	6 : structural engineering	gabion baskets					X									unknown	boat wash	important	P : lock island		2		**4**		
3	Sandford - UB	6 : structural engineering	riprap						X					X			unknown	boat wash	important	P : lock island		2		**4**		
3	Sandford - LB	6 : structural engineering	sheet piling						X					X			unknown	boat wash	important	P : lock island		2		**4**		
4	Clifton	1 : allowed natural adjustment	no works		X					X				X				river processes	moderate	R : public path*	**1**	2	3			
5	Clifton (1st)	5 : biotechnical engineering	geotextile + spiling										X				slab/cantilever	river processes	severe	FD : weir					**5**	6
5	Clifton (2nd)	6 : structural engineering	sheet piling										X				slab/cantilever	river processes	severe	FD : weir					**5**	6
6	Clifton	4 : bioengineering	spiling					X						X				boat wash	moderate	R : mooring facility	**1**	2	3			
7	Clifton	6 : structural engineering	sheet piling		X			X										boat wash	important	R : public path*		2		**4**		
8	Cleeve	5 : biotechnical engineering	geotextile + spiling + willow stakes		X												slab	boat wash/human activity	important	R : public path				**4**		
9	Cleeve	6 : structural engineering	gabion mattresses/riprap + geotextile		X												slab	boat wash/human activity	important	R : public path				**4**		
10	Goring	5 : biotechnical engineering	geotextile		X													boat wash/human activity	important	R : public path		2		**4**		
11	Mapledurham (1)	2 : management	fencing	X	X													animal activity	moderate	R : public path*	**1**	**2**	3			
11	Mapledurham (2)	4 : bioengineering	spiling	X	X													animal activity	moderate	R : public path*	**1**	2	3			
12	Caversham	4 : bioengineering	faggots		X					X				X			slab	river processes/boat wash	moderate	R : public path*	**1**	2	3	4		
13	Marlow	5 : biotechnical engineering	geotextiles	X	X													animal activity	moderate	R : public path*	**1**	2	3			
14	Marlow	4 : bioengineering	spiling		X													boat wash/human activity	moderate	R : public path*	**1**	2	3			
15	Cookham	6 : structural engineering	sheet piling + riprap		X							X					slab	river processes	important	R : public path				**4**	5	6
16	Cookham	4 : bioengineering	spiling		X	X		X						X				boat wash/human activity	important	R : public path		2		**4**		
17	Boulter's	6 : structural engineering	sheet piling + gabion baskets							X				X				river processes	severe	FD : weir					**5**	6
18	Egham - US	6 : structural engineering	gabion baskets								X			X				river processes	important	P : sluice & mooring facility		2		4	**5**	6
18	Egham - DS	4 : bioengineering	faggots															river processes	important	P : sluice & mooring facility		2		4	**5**	6
19	Egham	6 : structural engineering	gabion baskets		X		X							X	X			boat wash/human activity	moderate	R : public path* & amenity	**1**	2	3			
20	Shepperton	6 : structural engineering	gabion baskets		X								X	X			slab/cantilever	river processes	moderate	R : public path* & amenity	1			**4**		
21	Teddington - US	6 : structural engineering	riprap							X				X			local scour	river processes	important	P : weir		2		**4**	**5**	6
21	Teddington - DS	4 : bioengineering	faggots															river processes	important	P : lock island		2		**4**	**5**	6

UB = upper bank
LB = lower bank
US = upstream
DS = downstream

FD = flood defence
P = property
R = recreation
* denotes where there is sufficient land available to realign path

1 : allowed natural adjustment
2 : management
3 : relocation
4 : bioengineering
5 : biotechnical engineering
6 : structural engineering
[box] = optimum strategy from Environment Agency (1997) (shown in bold)

Appendix 6.5

Performance review of erosion control case studies

Case study no.	Reach	Strategy adopted & technique used	PERFORMANCE CRITERION (i): Optimum strategy recommended by Environment Agency (1997) framework	PERFORMANCE CRITERION (i): Performance ranking for compliance with Environment Agency (1997) recommended strategy (high/medium/low)	PERFORMANCE CRITERION (ii): Integrity of technique (intact/partial failure/complete failure)	PERFORMANCE CRITERION (ii): Performance ranking for integrity of technique (high/medium/low)	PERFORMANCE CRITERION (iii): Improvements to adopted technique	PERFORMANCE CRITERION (iii): Alternative technique	PERFORMANCE CRITERION (iii): Performance ranking for additional measures (high/medium/low)	PERFORMANCE CRITERION (iv): Relative impacts (high/medium/low /no impact)	PERFORMANCE CRITERION (iv): Additional mitigation measures	PERFORMANCE CRITERION (iv): Performance ranking for impact mitigation	PERFORMANCE CRITERION (v): Enhancements	PERFORMANCE CRITERION (v): Performance ranking for enhancements
1	Godstow	5 : geotextile + spiling	1	Low	Partial failure	Medium	Fencing	No action	Low	Low	x	High	x	Low
2	Godstow	6 : gabion baskets	4	Low	Intact	High	Regrade slope	Willows	Medium	Medium	x	Medium	x	Low
3	Sandford - UB	6 : riprap	4	Low	Intact	High		Planting (reeds)	High	Medium	Reed planting	Medium	x	Low
3	Sandford - LB	6 : sheet piling	4	Low	Intact	High		Willows	High	High	Reed planting	Medium	x	Low
4	Clifton	1 : no works	1	High	Intact	High			High	No impact	N/A	N/A	x	Low
5	Clifton (1st)	5 : geotextile + spiling	5	High	Partial failure	Medium	Regrade slope	Rock & fibre rolls + willows	Medium	Low	x	High	x	Low
5	Clifton (2nd)	6 : sheet piling	5	Medium	Intact	High	Regrade slope	Rock & fibre rolls + willows	Medium	High	x	Medium	x	Low
6	Clifton	4 : spiling	1	Low	Intact	High		No action	High	Low	x	Medium	x	Low
7	Clifton	6 : sheet piling	4	Low	Intact	High	Regrade slope	Willows	Medium	High	Marginal shelf with reed planting	Medium	x	Low
8	Cleeve	5 : geotextile + spiling + willow stakes	4	Low	Intact	High		Willows only	High	Low	x	High	x	Low
9	Cleeve	6 : gabion mattresses/riprap + geotextile	4	Low	Partial failure	Medium	Regrade slope	Willows	Medium	Medium	x	Low	x	Low
10	Goring	5 : geotextile	4	Low	Partial failure	Medium		Willows	High	Low	x	High	x	Low
11	Mapledurham (1)	2 : fencing	1/2	High	Intact	High			High	No impact	N/A	N/A	x	Low
11	Mapledurham (2)	4 : spiling	1	Low	Intact	High		No action	High	Low	x	High	x	Low
12	Caversham	4 : faggots	1	Medium	Intact	High		No action	High	Low	x	High	x	Low
13	Marlow	5 : geotextiles	1	Low	Complete failure	Low	Fencing	No action	Low	Low	x	Medium	x	Low
14	Marlow	4 : spiling	1	Low	Intact	High		No action	High	Low	x	High	x	Low
15	Cookham	6 : sheet piling + riprap	4	Medium	Intact	High	Regrade slope	Realign path + willows	Medium	High	Bank naturalisation	High	Fishing bay with reed planting	Medium
16	Cookham	4 : spiling	4	High	Intact	High			High	Low	x	High	Gravel beach recharge	Medium
17	Boulter's	6 : sheet piling + gabion baskets	5	High	Intact	High		Gabions only	High	High	x	Low	x	Low
18	Egham - US	6 : gabion baskets	5	Medium	Intact	High		Rock & fibre rolls	High	Medium	x	Medium	x	Low
18	Egham - DS	4 : faggots	5	Medium	Intact	High		Rock & fibre rolls	High	Low	x	High	x	Low
19	Egham	6 : gabion baskets	1	Low	Intact	High		No action	High	Medium	x	Medium	x	Low
20	Shepperton	6 : gabion baskets	4	Low	Intact	High	Regrade slope	Willows	Medium	Medium	x	Medium	x	Low
21	Teddington - US	6 : riprap	5	Medium	Intact	High		Rock & fibre rolls	High	Medium	x	Medium	x	Low
21	Teddington - DS	4 : faggots	4	High	Intact	High		Willows	High	Low	x	High	x	Low

UB = upper bank
LB = lower bank
US = upstream site
DS = downstream site
(1) = 1st of two techniques
(2) = 2nd of two techniques
(1st) = 1st technique used at site
(2nd) = 2nd technique used at site

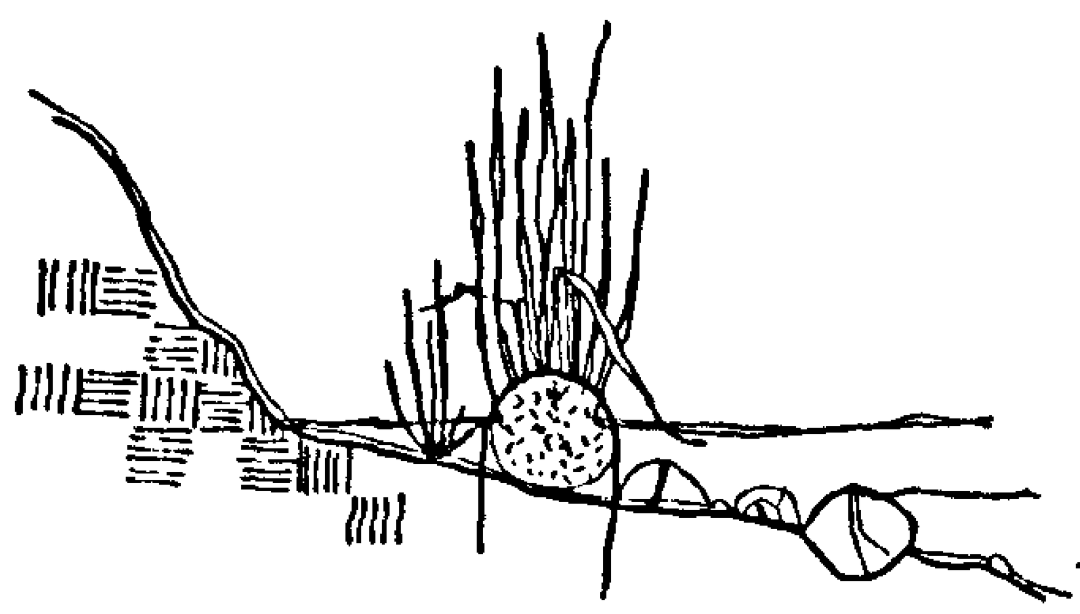
Erosion control strategies:
1 = allowed natural adjustment
2 = management
3 = relocation
4 = bioengineering
5 = biotechnical engineering
6 = structural engineering

APPENDIX 7

Appendix 7

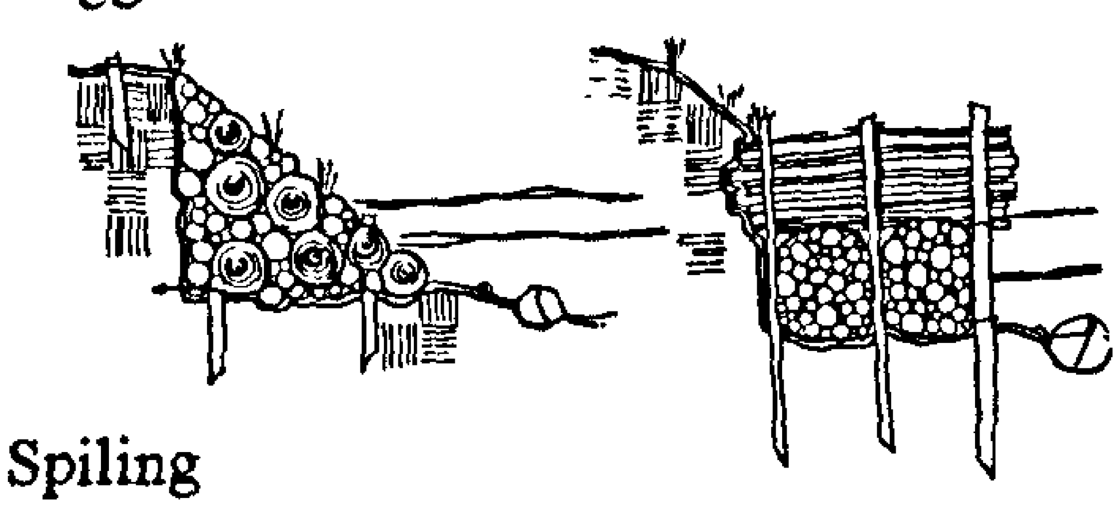
Examples of bank erosion control techniques for use along the River Thames

<u>Marginal planting</u>: eg. reed planting in coir or wire rolls to protect against boat wash and low flow velocities.

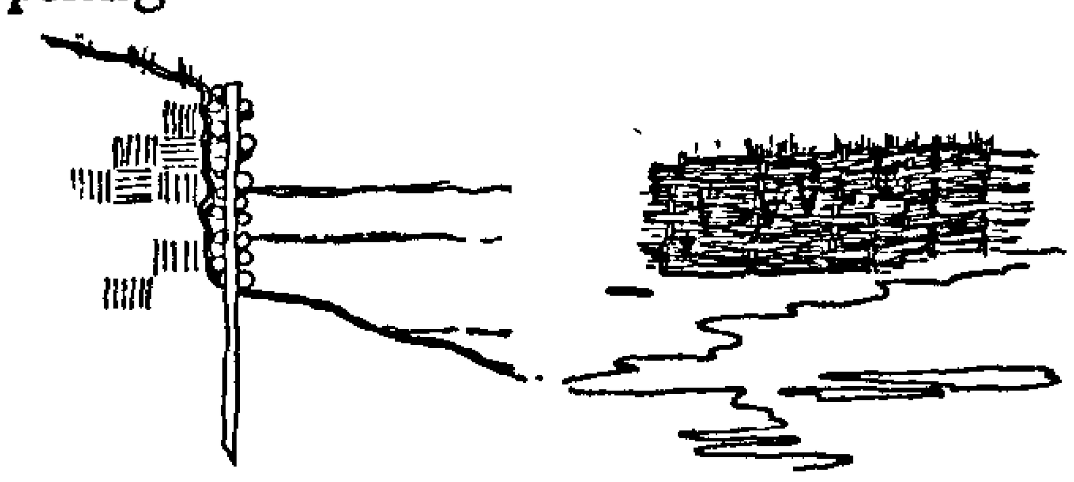


<u>Vegetative structures</u>: eg. faggots and spiling to protect against moderate flow velocities and encourage deposition within the vegetative structure and provide long term root anchorage.

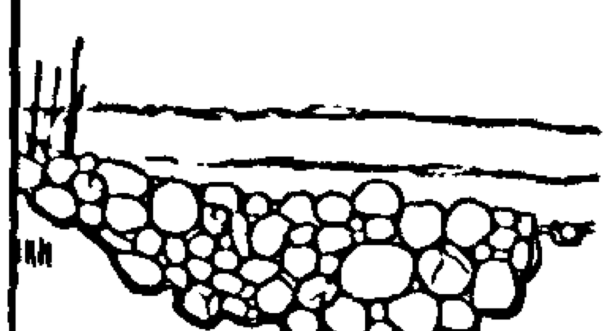
Faggots



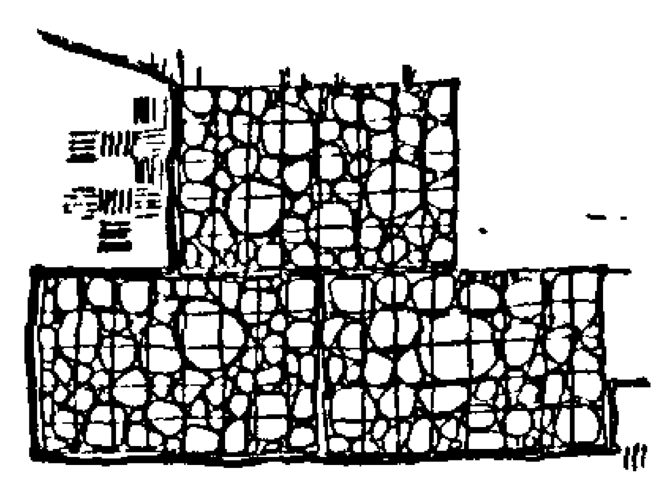
Spiling



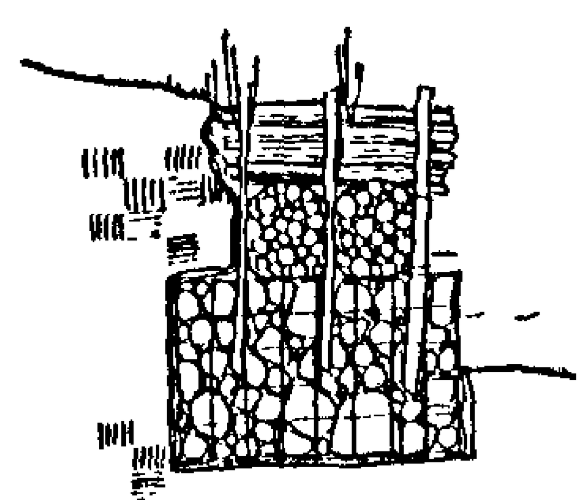
<u>Structural engineering techniques</u>: eg. riprap and gabion baskets offer the potential for replanting and, to some extent, recovery of the river margins. These should be selected in preference to other structural engineering techniques.



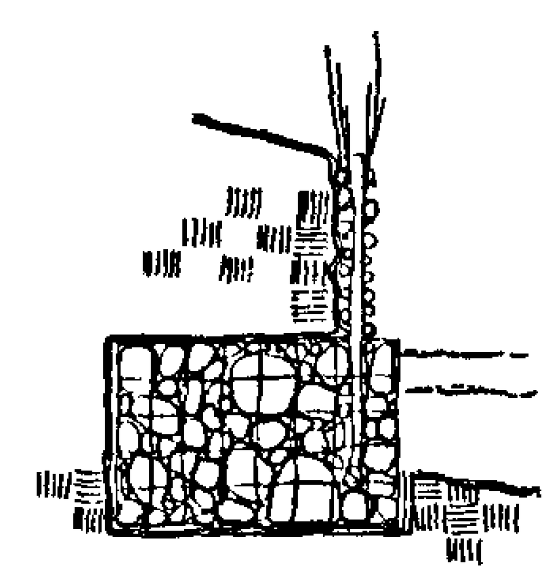
Loose stone riprap



Gabion baskets

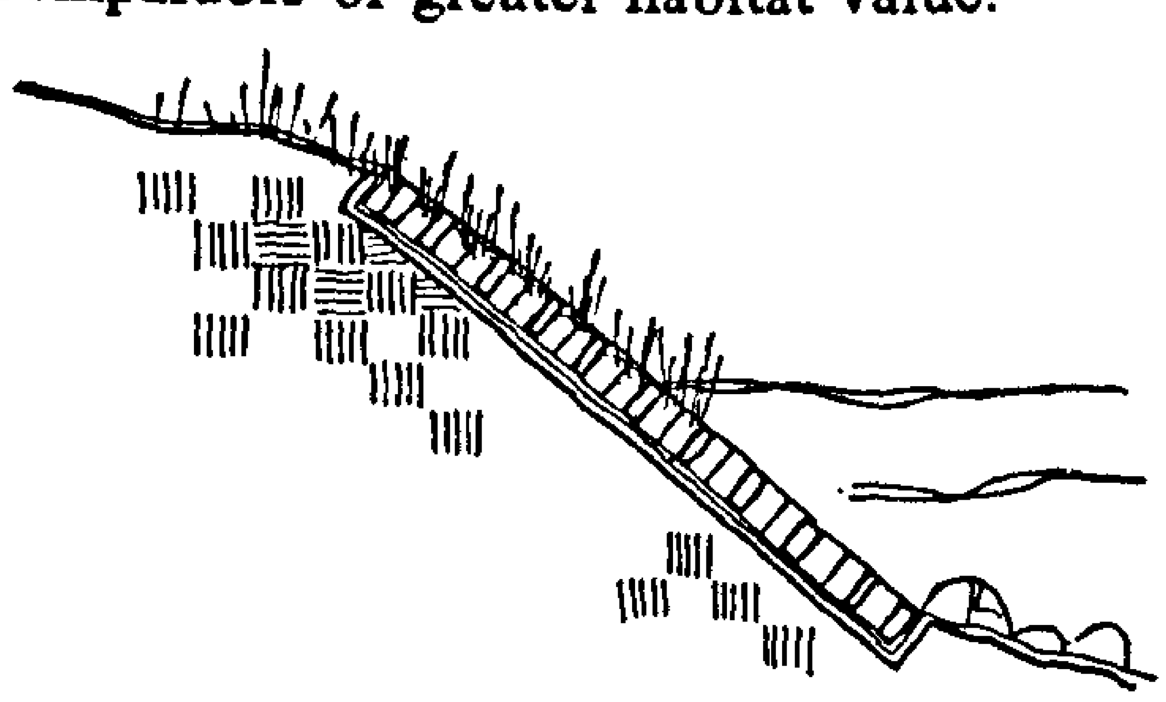


Gabions with faggots

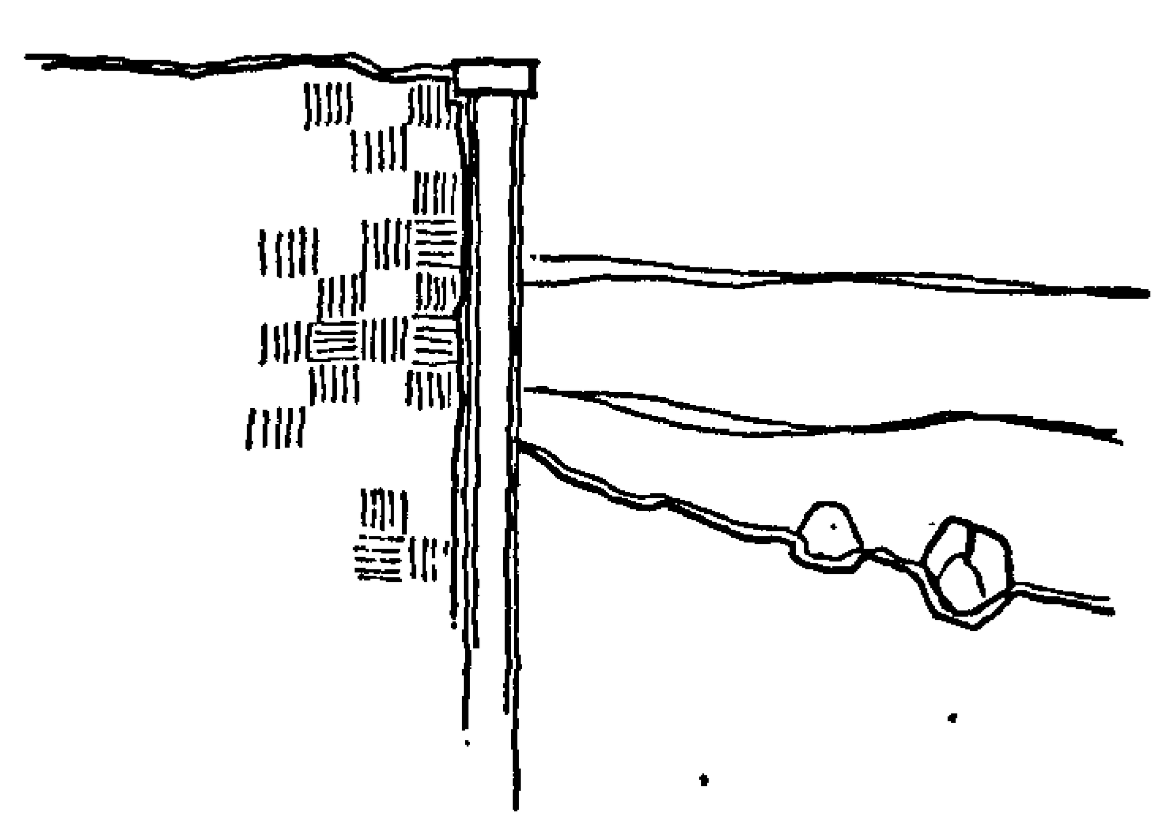


Gabions with spiling

<u>Biotechnical engineering techniques</u>: eg. open cellular concrete and geotextiles, although gabions and riprap offer comparable or greater habitat value.



<u>Structural engineering techniques</u>: eg. sheet piling, with limited habitat potential.



Sketches courtesy of Environment Agency, Thames Region /D. Woodruff