Project 336

BANK EROSION ON NAVIGABLE WATERWAYS

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National Rivers Authority

BANK EROSION ON NAVIGABLE WATERWAYS

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GLOSSARY

The study of river banks uses terms, concepts and jargon that will be unfamiliar to non-specialists. To aid in reading and understanding this report, this section presents a glossary of important words and terms.

Alluvial River A river with a "self formed" channel. The size and shape (morphology) of the channel are the result of the entrainment, transport and deposition of sediment from the unconsolidated materials forming the bed and banks.

Angling - Recreational Rod and line fishing for coarse or game fish from locations selected by the anglers at their discretion. While some spots are certainly more attractive than others, recreational angling does not concentrate activity at specific locations in the the that competition angling does.

Angling - Competition Rod and line fishing from fixed locations marked by "pegs". Anglers are randomly assigned to evenly spaced pegs along the bankline which are used repeatedly in competition fishing. Activity is concentrated exclusively at these locations. Through time pegs tend to become worn through vegetation destruction and trampling damage to the bank.

Bank Erosion The process by which individual particles or aggregates of bank material are detached from the bank and removed by the river or some other erosive agent.

Bank Failure The sudden collapse of a river bank due to inability of the soil to resist stresses imposed by the weight of the bank and/or the pore water pressure within the bank.

Bank Retreat The recession of a bankline into the flood plain due to either bank erosion acting alone, or together with bank failure through collapse followed by basal clean-out of failed debris.

Bankfull Flow Flow which just fills the channel without over-topping the banks and inundating the flood plain. Often taken to be the dominant or channel forming flow in an alluvial river.

Basal Endpoint Control Concept linking the rate of fluvial scour at the toe to the rate of bank retreat. There are three possible states of basal endpoint control:

> **Basal Scour,** where sediment removal exceeds supply so that toe scour and undercutting occur. Decreased bank stability due to toe scour increases the rate of retreat tending towards the second state.
>
> **Dynamic Equilibrium,** where rates of sediment removal by the flow and supply from bank erosion and failures are matched so that the bank maintains its profile geometry and under goes parallel retreat at a rate determined by the rate of fluvial scour.
>
> **Berm and Beach Building,** where the sediment supply exceeds the removal so that sediment accumulates at the toe. The increased bank stability due to toe accumulation reduces the rate of supply, tending towards the second state.

This concept demonstrates that in general it is the rate of fluvial entrainment of bank material and bank failure debris that governs the long-term rate of bank retreat and width adjustment in alluvial rivers.

Basal Clean-out Removal from the bank toe of bank failure debris and soil loosened by weathering.

Berm or Wet Berm An accumulation of predominantly cohesive sediment at the toe of a receding bank, due to basal accumulation of bank failure debris. The berm produces a convexity in the bank profile and may support riparian and emergent vegetation.

Boat Wash The waves, water level changes and currents generated by passage of a vessel along an inland waterway. Includes the bow wave, draw down (in relatively narrow/shallow waterways), stern wave and propeller wash.

Deposition The laying down of sediment due to the inability of the flow to continue to transport it as sediment load. Deposition usually occurs in along the channel margins in slack water areas where stream energy is low.

Dominant Discharge The flow rate which plays the most significant role in forming an alluvial channel. Usually approximates to bankfull discharge and has a return period of one to two years.

Dynamic Equilibrium The condition where the amounts of sediment entering and leaving a river reach or bank zone are balanced so that there is no net change in bed level through time. A river in dynamic equilibrium may migrate across its flood plain through retreat of one bank which is matched by advance of the opposite bank. A bank in dynamic equilibrium retreats at a steady rate and with no pronounced change of bank geometry through time.

Fluvial Entrainment The process whereby particles are incorporated into the body of flowing water because the erosive shear stress applied by the flow to the solid boundary overcomes the resisting strength of the soil. Entrainment is promoted by weathering processes such as freeze/thaw that weaken and loosen the soil surface.

Fluvial Geomorphology Study of the dimensions, cross-sectional shape and planform pattern of river channels and the processes responsible for the formation and evolution of alluvial channels.

Fluvial System The channel portion of the drainage network in a river basin including the flowing water, mobile sediment and the materials forming the bed and banks.

Freeze/Thaw A weathering process in which water in pores in the bank first freezes and expands, causing loosening of the bank soil, and then melts, carrying away the loosened particles. Freeze/thaw is especially effective on the face of steep, unvegetated banks.

Sediment Load Solid particles being transported by the river due to catchment erosion and fluvial entrainment from the bed and banks.

Sinuosity Measure of the degree of meandering of a river. Ratio between channel length and straight line distance between two points on the river.

Spending Beach A low angle accumulation of predominantly noncohesive sediment at the toe of a receding bank, due to basal accumulation of bank failure debris. The level of flow and wave erosion on a spending beach prevents the establishment of permanent vegetation.

Stream Power Proportional to the product of flow discharge and channel slope. Stream power is an excellent measure of the ability of the flow to do work on (and hence dynamically adjust) the channel through sediment entrainment, transport and deposition.

Steady State Flows of river water and sediment load are not zero, but bank and channel form do not change with time.

Toe Scour Fluvial erosion of the river bed adjacent to the bank that leads to an increased bank height and side slope angle. Toe scour may lead to bank failure if the bank soil is unable to support the stresses imposed by the weight of the bank.

Undercutting Erosion of the lower bank that leads to an increased side slope angle and in extreme cases to a cantilevered or over-hanging bank. Undercutting usually leads to bank failure when the bank soil is unable to support the stresses imposed by the weight of the bank.

Undermining Erosion of the lower bank produces a cantilever or overhang in the upper bank which eventually fails when its weight overcomes the tensile and beam strength of the soil.

EXECUTIVE SUMMARY

Some bank erosion occurs along all natural and most artificial waterways and as part of the operation of the fluvial system. Rates of natural bank erosion in Britain are usually quite low and most serious erosion can be attributed to acceleration by some human activity or intervention. In many situations bank retreat is acceptable and, in fact, limited bank erosion plays a beneficial role in aquatic and riparian ecosystems through removing old bank vegetation, making space for new species to become established and providing habitat for riverside fauna. Hence, bank erosion is in itself not necessarily a bed thing and not every case of bank erosion requires treatment.

However, in circumstances where bank erosion poses an unacceptable threat to human activities or structures along the river, steps must be taken to reduce, or eliminate, bank retreat. When considering the steps that should be taken it is vital that the cause, severity and extent of the bank erosion problem be assessed accurately before the solution is selected. This requires a comprehensive survey of the problem, using historical, documentary and field reconnaissance sources of data that extends beyond the specific site in question in order that the problem can be assessed within the context of the entire fluvial system. Often in the past bank stabilization schemes have been undertaken with the sole purpose of preventing bank erosion at a particular location. Experience shows that solutions based on this restricted, site specific treatment of bank erosion tend to trigger problems elsewhere in the system and are inconsistent with a holistic, multi-functional approach to river management.

In developing a policy for the management bank erosion on navigable rivers four guiding principles have been established that set out a framework for appropriate, multi-functional responses to perceived problems:

1. Identify the cause of the bank erosion problem. If it is purely due to natural erosion as part of the fluvial system then, if possible, allow it to continue. Avoid intervention unless bankline retreat is absolutely unacceptable;

2. Where retreat cannot be allowed, and especially if the cause is human activity, seek a solution through active bank management, and only intervene with structural protection when this alternative approach is not acceptable;

3. When active management or structural intervention are justified, match the scope, strength and length of bank covered by the solution to the cause, severity and extent of the problem. Active bank management and soft engineering, although desirable, are not appropriate for locations of intensive bank attack. Every unsuccessful managerial or soft solution detracts from the credibility of the approach and damages the image of alternative solutions.

4. When reacting to a bank erosion problem and deciding on a course of action, bear in mind the responsibility to balance conflicting goals in river management to achieve the optimum solution in terms of the four E's: Efficacy, Economy, Engineering and the Environment.

Where a structural solution that involves physically protecting the bank is apprpriate there are now a wide range of designs and materials that may be used. These range from hard engineering materials such as concrete and steel used on firm foundations, to softer materials such as geotextiles, based on flexible footings. Increasingly, live vegetation is being promoted as an integral component of bank stabilization schemes. Vegetation may be used to mask hard structures in order to make them more acceptable aesthetically and environmentally, but the potential to use vegetation to provide part of the structural protection is now being recognised. Many of the techniques and plants currently being developed have actually been rediscovered as they were in widespread use two centuries ago and actually pre-date the use of concrete and steel. In this respect, it is a mistake to think that hard engineering is the traditional solution to bank erosion problems and that vegetative solutions are innovative. It is, however important to recognise that soft solutions are not appropriate in every situation and that each case requires careful consideration based on the best information available and a full assessment of the causes, severity, threat posed and extent of the erosion problem.

The policy and approach recommended here rests on accurate assessment of bank erosion processes that requires expertise in fluvial geomorphology and river mechanics. As such expertise is not routinely available in all regions there are implications for staff recruitment and training. Also, application of the four guiding principles will lead inevitably to a policy of 'managed retreat' at some locations, where intervention through active bank management or structural protection is found to be unjustified. It is essential that this policy be explained to landowners and the general public alike in order to win over their hearts and minds.

The potential benefits of adoption of the approach recommended here are the realisation of economic savings through reductions in the costs of capital schemes, without a reduction in the effectiveness of overall river stabilization works and with improvements in the qulaity of both river aesthetics and riparian habitats.

KEYWORDS

Bank erosion	Bank protection	Bio-engineering	Boat wash
Geomorphology	Navigation	Navigable waterways	Revetments
Riparian Zone	River conservation	River management	River stabilization

1. INTRODUCTION

1.1 Terms of reference

The Terms of Reference (ToR) for this project set out 5 specific objectives. These are:

1. To determine the rates, spatial distributions and temporal variations of bank retreat primarily on the River Thames above Teddington Lock (but also on selected navigable rivers in other NRA Regions) considering the regional contexts of bank retreat and comparing the results with those of other studies;

2. To investigate the factors controlling bank erosion including bank properties, external influences and established theories;

3. To consider alternative and appropriate management techniques for bank erosion, recognising that management involves more than engineering and drawing on examples where management can be shown to have been effective;

4. To turn the consideration of management techniques into a management strategy that includes both general principles that are transferable to other Regions and specific recommendations for the navigable River Thames;

5. To produce, in a series of documents, operational level guide-lines for use by staff concerned with processing land drainage consents, commenting on planning applications made to Local Authorities and dealing with related work in the recreation, conservation and navigation divisions.

1.2 Background

The objectives set out in the Terms of Reference were addressed through a two year study that combined elements of:

* field monitoring, mapping and investigation of bank erosion at specific sites on selected navigable rivers;
* laboratory testing of bank material samples;
* assimilation and analysis of historical and archive data on river flows, climate and river use;
* literature searches and reviews;
* database development.

Given the emphasis in the ToR on the navigable Thames, the major effort was directed toward that waterway. Study sites were also established on rivers in the Anglian, Severn-Trent and Southern Regions of the NRA. A list of study sites is given in Table 1.

Sites were selected on the basis of field inspection by the project investigators and valuable advice from local and regional NRA staff. Sites were chosen to represent conditions in reaches known to display the variety of the bank erosion problems and solutions typically occurring along the waterway.

Table 1 Study Sites Monitored in the Field Programme

Region	River	Monitoring Site
Thames	Upper Thames	St Johns
	Middle Thames	Upper Wallingford
		Lower Wallingford
		Goring
	Lower Thames	Laleham
		Upper Chertsey
		Lower Chertsey
Southern	Medway	Hartlake
		Branbridges
		Teston
Anglian	Great Ouse	Bridge Farm
		Gravel Bridge
	Ant	Hunsett Mill
	Yare	Brundall
	Bure	Upton Mill
Severn-Trent	Trent	Upper Gunthorpe
		Lower Gunthorpe
		Upper Hoveringham
		Lower Hoveringham

The limited timescale of the project allowed for only one full year of monitoring. It is, therefore, unlikely that the rates of erosion observed in the study will be meaningful in terms of medium to long-term management strategy. Ideally, monitoring should now be continued for several years in order to establish the magnitude of both long-term, averaged and short-term, maximum rates of bank erosion.

However, used with sound judgement and experience, the results of this study should be useful in helping to understand and explain bank erosion on navigable rivers and in supporting development of a framework for improved selection of appropriate types of protective solution, based on a sound management strategy and policy approach.

The broad scope of this report is intended to promote cross-functional management of bank erosion problems within national and regional policy frameworks. It also has the potential to form a useful contribution to a cross-organisational handbook, should the agencies responsible for navigable inland waterways decide to produce such a document in the near future.

1.3 Erosion processes and instability mechanisms: earth surface processes responsible for bank problems

Problems of bank retreat may occur as the result of a wide variety of erosion processes and instability mechanisms. When attempting to deal with a bank problem it is necessary first to understand the processes and mechanisms responsible for the problem. This is because it is essential that the solution deals successfully with all significant processes and mechanisms, and not only with the most obvious or visible ones. A hard engineering solution often achieves this despite a lack of detailed understanding of the problem because it usually protects and stabilizes the bank with a substantial factor of safety.

However, there are heavy environmental impacts on the aesthetic and habitat value of the bank and, unless carefully designed, hard protection may trigger bank problems on adjacent or nearby unprotected banks. The successful application of both soft protection and managerial solutions usually demands a full understanding of the problem. Similarly, a decision to allow erosion to continue through "managed retreat" must be based on a sound analysis of past and present erosion and a reliable prediction of future developments with and without intervention.

Bank problems rarely result from the operation of a single process of erosion or mechanism of instability. In fact, bank retreat is usually the result of complex interactions between a number of processes and mechanism that act on the bank either simultaneously, or in sequence. These may be grouped into three broad categories:

1. Erosion Processes which detach, entrain and transport individual particles or assemblages of particles away from the face of the retreating bank;

2. Failure Mechanisms which lead to collapse of all or part of the bank;

3. Weakening Processes which operate on and within the bank to increase its erodibility and to reduce its geotechnical stability.

Table 2 presents a list of failure mechanisms, processes of erosion and processes of weakening, together with a brief outline of their significance and impact on bank retreat and related problems.

Table 2. Classification of Bank Erosion Processes and Mechanisms

This Table is currently being finalised in conjunction with the results presented in the Project Record.

1.4 Basal endpoint control: The key to understanding bank problems

The various processes and mechanisms that may be responsible for destabilizing a river bank make bank analysis a complex issue. However, if instability and retreat are sustained, and bank problems are chronic, then a geomorphological concept known as *basal endpoint control* demonstrates that scour and removal of sediment at the toe of the bank is the key to understanding bank retreat and identifying the root cause of a problem. To explain why, it is necessary to visualise the sediment movement system in the near bank zone of the river.

Figure 1 shows the near bank zone schematically. Sediment may be supplied to the toe of the bank both from upstream or from the bank. Bank sediment is input either due to bank erosion or bank failure. Sediment may be removed from the toe either downstream, or laterally towards the centre of the channel by secondary currents or wave action. These sediment fluxes allow three states of sediment balance or imbalance at the toe to exist: output>input; output=input, and; output<input.

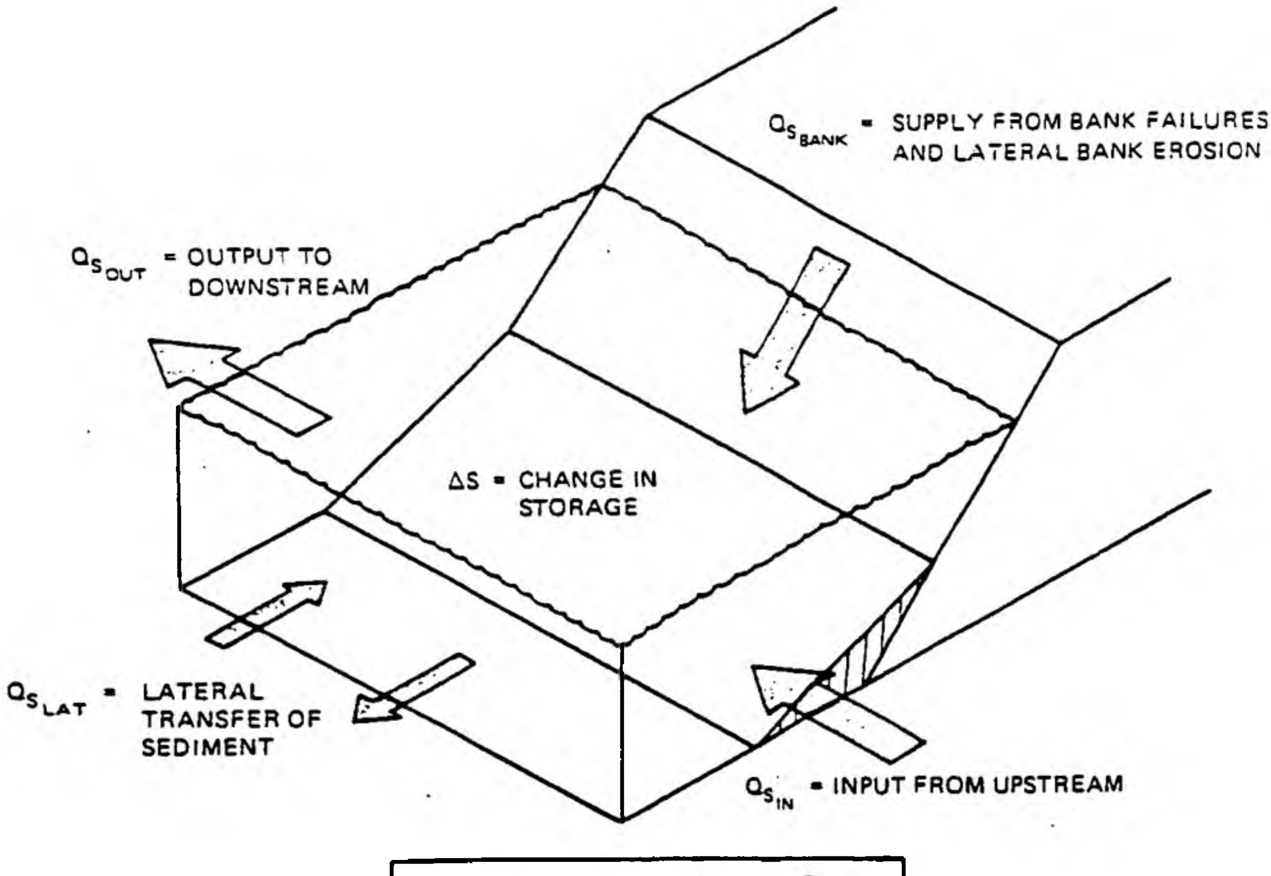
If the rate of removal is greater than supply (output>input) then toe scour and undercutting occur. This reduces bank stability and triggers mass failures that increase the rate of sediment supply and, hence, bank retreat. The rate of retreat accelerates tending towards a dynamic equilibrium where the retreat rate is matched to the rate at which sediment is removed from the toe zone by current and wave processes.

If sediment inputs and removal are balanced (output=input) then there is no overall scour or deposition at the toe and the profile of the bank does not change with time. The rate of bank retreat is matched to the rate of toe sediment removal by currents and waves. This represents a form of dynamic equilibrium with the bank profile shifting through parallel retreat.

If the rate of removal is less than the bank input (output < input) then sediment accumulates at the toe through the growth of a low angle berm, or spending beach. This tends to protect the bank behind it and will decrease the rate of input of bank sediment by reducing the rate of retreat. Hence, the retreat rate decreases, tending towards a value matched to the rate at which sediment is removed from the berm or beach by current and wave processes.

Recognising the state of basal endpoint control of a problem bank, through examining the bank profile and the sediment balance at the toe, gives useful insights into the operation of erosion processes and failure mechanisms and, hence, the cause of the problem. For example, if a bank is being actively undercut due to excess erosion over sediment supply at the toe, then significant river currents and/or waves are causing an accelerating problem and a soft solution alone will have very little chance of success. Experience shows that in cases of undercutting either some form of structural toe protection is required, or the energy of waves and currents adjacent to the bank must be substantially reduced by flow deflection or bank re-profiling. This illustrates how recognition of the state of basal endpoint control assists in the correct identification of the cause of the problem and the best approach to solving it.

The theme of using careful observation of bank form and process to establish the cause of the problem, together with guidance on the selection of an appropriate solution for different causes and types of problem, provides the methodological basis of this report.



$$\Delta S = Q_{S_{IN}} - Q_{S_{OUT}} \pm Q_{S_{LAT}} + Q_{S_{BANK}}$$

Figure 1. Sediment Movement into and out of the near bank zone. The sediment balance determines the rate of toe scour or spending beach accumulation at the foot of the bank and this ultimately deterimines the rate of bank retreat.

2. ASSESSMENT OF BANK EROSION PROBLEMS

2.1 Geomorphic context: Bank erosion as a natural process

All rivers transport a mixture of water and sediment along their courses. Most of the sediment load is usually derived from sources outside the channel, such as fields and hillslopes draining to the river that are subject to erosion by processes like rain splash, rilling and soil creep. Sediment is also derived from within the channel through fluvial entrainment of material from the bed and banks. Through these processes, combined with subsequent deposition of the sediment so generated, the river is able to alter the dimensions and shape of its channel.

Over a period of time, the channel evolves to a point where it is morphologically adjusted to the dominant discharge and associated sediment load input from upstream. In this case the bankfull capacity of the channel is close to the dominant discharge. It is then said to be in dynamic equilibrium. However, as catchment and channel conditions are themselves constantly changing stable equilibrium is seldom, if ever, attained. As a result, rivers constantly adjust their channel form in the hunt for an elusive balance between the flow of water and the erosion, transport and deposition of sediment.

Depending on the level of stream power possessed by the river, channel adjustments may be more or less apparent. Many British rivers have relatively low stream powers (Brookes, 1988) and consequently their natural channel adjustments may be so subtle as to be practically imperceptible to the untrained eye. For example, natural maximum bank erosion rates on British rivers are of the order of centimetres or tens of centimetres per annum (Thorne, 1978; Lewin, 1981) while those found elsewhere in the world, in high energy environments, may be two or three orders of magnitude greater than this (Thorne and Russell, 1993). However, it is still a fact that channel adjustments involving bank erosion, bank deposition and resulting bankline movements are actually an integral part of the natural functioning of British rivers.

Adjustments to channel form take place both through vertical scour and fill of the bed (degradation or aggradation) and through lateral erosion and deposition of the banks (changing width or planform pattern). In Britain the potential for vertical adjustments is severely limited by constraints imposed by the terrain, the geology and human management in the form of river regulation structures such as weirs and sills. Hence, much of the significant channel change that does take place is concentrated in the lateral dimension and is achieved through width and planform (sinuosity) adjustment. Viewed in this context, bank erosion can be seen as an essential and ever present component to the natural operation of the fluvial system.

The natural tendency for a river to erode, transport and deposit sediment, and so constantly adjust its channel form, must be borne in mind when thinking about river management. Those in authority should think long and hard before embarking on a programme of bank protection that attempts to eliminate natural bank erosion. Once begun, such programmes are very difficult to stop because as the proportion of unprotected bank decreases, the rate of erosion on the remaining erodible bank tends to increase, so that further work becomes unavoidable. The inevitable out-come of any serious attempt to control natural bank erosion is a fully trained river, with almost continuous bank protection, high capital and maintenance costs and heavy morphological, environmental and aesthetic impacts.

2.2 Human impacts on the rate and extent of bank erosion

If the natural processes of fluvial erosion, transport and deposition are disturbed by human intervention, the river reacts by attempting to adjust its channel form to account for the impacts of the intervention and by seeking alternative erosional sources and depositional sinks for its sediment load. At the basin scale, changes in catchment land-use that significantly alter the volumes and time distributions of water and sediment input to the channel have the potential to destabilize the entire fluvial system. At reach scale, channel stabilization that prevents dynamic adjustment at one river site or reach may cause instability to commence somewhere else. For this reason it is not uncommon to find severe erosion in locations adjacent to or opposite lengths of protected bank. At site scale, a poorly chosen bank alignment, or a badly sited structure may induce flow patterns that generate rapid, local bank retreat. Human impacts can, therefore, affect both the intensity (time rate) of bank erosion and its extent (spatial range) along the river's course, at a variety of scales.

Generally, when dealing with a bank erosion problem, it is essential to match the scale of the solution to the scale of the problem. In this respect, local schemes and structures are only really applicable to local problems. Also, erosion that is directly attributable to a human cause, or causes, is more amenable to successful control than that which is a component of the natural fluvial system. If the erosion is human in origin, then measures to eliminate the cause through management of human activities or access may well be more attractive than structural solutions that attempt to protect the bank.

In practice, it is not always easy to identify whether the cause of erosion is a local, reach scale or a system wide phenomenon. Also, it is often difficult to differentiate between natural bank erosion and that which has either been triggered or accelerated by human activities. Yet in many cases it *is* possible to attribute a bank erosion problem to a particular cause and, therefore, to classify it firstly as being of local, reach-scale or system-wide extent and, secondly, as being of either natural or human origin. These are very helpful steps in the selection of the best management approach to dealing with a bank erosion problem and some guidance on the approach adopted in identifying, assessing and classifying causes of bank erosion is appropriate.

2.3 Techniques for bank erosion problem identification, assessment and classification

2.3.1 Background

Identification and classification of a bank erosion problem should be based on assessment of all available data and information. Documentary and archival information helps to establish the history of bank problems at a site. Useful background material can usually be obtained from old map series with reliable dates, aerial photographs and appropriate NRA, County and Municipal Council records

Direct observations in the field are invaluable in the proper assessment of any bank problem. Efficient performance of field observations and their interpretation can be divided into 5 stages, dealing with each of the following aspects in turn:

1) Scope and purpose of bank assessment;

2) Channel sketch map;

3) Bank survey;

4) Identification of bank erosion and/or instability problem, and;

5) Examination of toe-sediment balance of the bank.

A complete and thorough evaluation of the bank, its location and its morphological dynamics lies at the heart of problem assessment and forms the selection of appropriate approaches to managing the problem or selecting the appropriate stabilization strategy.

The remainder of this section of the report deals, in turn, with each of the five stages defined above, and sets out the most crucial elements in bank erosion assessment and management. In Appendix A, a set of record sheets is presented. This can be used to aid field observation and interpretation of a bank problem and forms a useful, permanent record for future reference and post-project appraisal. Some training in the techniques involved would be essential (and this is addressed in the *Note on Policy* from this project), but experience has shown that with practice individuals quickly acquire the basic skills required to make reliable records and notes.

It is important that each stage be addressed independently. For example, geotechnical stability is not addressed until Stage 4. Users should not allow the presence or absence of failures influence their observations in earlier sections dealing with other bank characteristics.

The accumulation (or lack of accumulation) of loose bank debris and sediment at the toe of the bank is a very significant and important morphological feature of alluvial channels because it helps to indicate the state of basal endpoint control (see Section 1.4). Consequently, it is dealt with in stage 5, separately from the intact bank.

2.3.2 Section 1 - Scope and purpose

Field time is expensive and to be cost-effective an effort should be made to acquire, before setting out, the relevant Ordnance Survey map(s), a geological map and, if available, an aerial photograph of the study reach. The setting revealed by these simple sources of aerial data can be crucial to understanding the nature and wider, spatial context of a bank problem.

In selecting the team to undertake the field trip, a person with local experience and background knowledge of the location is practically essential. The field visit is only able to present a snapshot in time and the value of the record is enhanced by comments from someone with past experience of the site. At least one member of the team should have had some training in geomorphology and some prior experience of using the bank assessment sheets.

Experience shows that the whole exercise goes better when the field team has a clear understanding of the problem being addressed and the purpose of the field work. Consequently, a briefing to appraise the team of the problem and the main issues must be be given before the field assessment. The team must record a problem statement and note the purpose of the assessment at the out-set, together with details of the logistics of the fieldtrip. Not only does this concentrate the minds of the team, but it helps to put the results into context when subsequent investigators use the bank assessment document as a historical record of conditions at the site.

2.3.3 Section 2 - Channel site map

The first task is to explore the river and riparian zone around the problem location and establish the lie of the land, significant natural and artificial features of the flood plain, and the morphology of the channel. These features are best sketched on a site map together with representative cross-section(s). Space is provided for both in Section 2 of the Bank Assessment Record Sheet. The site map may be sketched by hand, but often it is much better to work directly on to an Ordnance Survey map of appropriate scale for this purpose. It is important to use the symbols given in the key in order that features noted in one survey can be properly interpreted by different operators in subsequent surveys. Also, the locations of any site photographs must be noted on the map if they are to form a really useful record for future reference.

2.3.4 Section 3 - Bank survey

The second task is to describe the form and features of the river bank in terms of the bank characteristics (including material properties and layering, profile geometry, the bank protection status and presence of cracks or fissures), bank structures and bank vegetation. Each of these characteristics is of fundamental importance to selection of appropriate techniques to solve the bank problem. Space is provided for notes on important morphological features of the bank.

2.3.5 Section 4 - Bank problems

The fourth task is to establish the location, extent and severity of the particular problem experienced by the bank at the site, or along a river reach. Bank erosion processes and geotechnical instability are treated separately in line with the established fact that each requires separate consideration when selecting appropriate solutions. This Section contrasts with the previous ones in that as well as keen observation and recording of features, a degree of interpretation is required through which geomorphic process is inferred from bank form. In the record sheets observations are noted separately from interpretations and the team can assign a level of confidence to their interpretative record based on their degree of experience and self assurance.

2.3.6 Section 5 - Bank Toe Condition

This section concentrates observations and their interpretation on a crucial area - the toe of the bank. The form of the bank profile at the toe, the presence or absence of debris from bank erosion or failures and the type and age of vegetation are recorded. These observations give important clues on whether the bank toe is being actively undercut by the river currents and/or wave action, or is accumulating sediment due to retreat that is being driven by processes operating within or behind the bank. Identification of whether the driving processes of retreat are derived from the river side or the flood plain side of the bank is absolutely essential if managerial or soft protection solutions to the problem are to be attempted.

2.3.7 Section 6 - Bank map and profiles

Completion of the final section actually runs in parallel to Sections 3, 4 and 5. It consists of detailed field sketching of the bankline to produce a bankline map and representative profiles that shows the spatial relationship between various morphological forms and features noted on the record sheets.

Good use may be made of photographs to supplement the information sketched and noted, however, experience shows that that the value of photographs is increased enormously if the locations and orientations of all site photographs is shown on the site and bankline maps. This is helpful in examining photographs afterwards, and it is invaluable on subsequent site visits, when attempting to use the photographs to identify channel and bankline changes.

2.3.8 Summary sheet

The summary sheet draws together the observations and interpretations to produce a synopsis that can be used by planners, policy makers, river managers and designers of bank protection structures. The summary sheet is divided into short statements describing: the general condition of the bank and the location, the extent and severity of bank problems; the primary and tertiary processes and mechanisms driving bank retreat; probable cause(s) of the problem and; suggestions for solution through changes of bank management or appropriate structural intervention.

2.3.9 Conclusion

The disciplined and detailed approach to field work for bank assessment is the basis for sound identification and characterisation of the site, the bank and its problems. The methodology for observing, recording and interpretating bank form and process may at first sight appear overly complex. In fact, experience has shown that the methodology can be mastered quickly and that it does provide suitable documentary information from which decisions can be made regarding the most appropriate approach to dealing with the bank problem.

3. BANK EROSION POLICY AND MANAGEMENT

3.1 Guiding principles

This section deals with the policy and management framework for consideration of bank problems. It is important that a coherent and carefully considered strategy be developed for a river, so that there can be consistent reaction to problems as they arise. While every river and, even each bank erosion problem, is to some extent unique and requires an individually tailored plan, a piecemeal or ad hoc system whereby each case is treated in isolation must be avoided. This section presents broad guidance for deciding how to react to a bank erosion problem by putting forward four guiding principles:

1. Identify the cause of the bank erosion problem. If it is purely due to natural erosion as part of the fluvial system then, if possible, allow it to continue. Avoid intervention unless bankline retreat is absolutely unacceptable;

2. Where retreat cannot be allowed, and especially if the cause is human activity, seek a solution through active bank management, and only intervene with structural protection when this alternative approach is not acceptable;

3. When active management or structural intervention are justified, match the scope, strength and length of bank covered by the solution to the cause, severity and extent of the problem. Active bank management and soft engineering, although desirable, are not appropriate for locations of intensive bank attack. Every unsuccessful managerial or soft solution detracts from the credibility of the approach and damages the image of alternative solutions.

4. When reacting to a bank erosion problem and deciding on a course of action, bear in mind the responsibility to balance conflicting goals in river management to achieve the optimum solution in terms of the four E's:

   Efficacy, Economy, Engineering and the Environment.

The remainder of this section expands and explains each of the four guiding principles in turn.

3.2 First principle: Identify the problem

Problem identification is the key to applying the first guiding principle. This should be undertaken using historical, documentary and field data collection methodology described in Section 2.3. The summary sheet on bank assessment, taken together with other information from reliable sources, should allow characterisation of the bank problem by answering the following question:

Q1. Is the problem part of the natural geomorphic processes in an alluvial channel?

If the problem is not associated with any human activity or artificial structure, but is a result of natural bank erosion due to the geomorphic activity of the river then it is doubtful if attempts to control it through local river management or structural intervention are wise. Some bank erosion is inevitable along the course of an alluvial stream, and environmentally this is, in fact, desirable as it eradicates old and overly mature riparian vegetation, leads to renewal of the bankside environment and creates important mammal and bird habitats through the formation of river cliffs in eroding banks. Unless the threat posed by natural bank erosion is so serious that it simply cannot be ignored, then local intervention should be avoided. In general, treatment of natural bank erosion is best considered at basin scale through Integrated Basin Management (IBM) and local solutions must be nested within that framework.

3.3 Second principle: Gauge the threat posed by bank erosion

The second guiding principle recognises that there is a certain amount of risk associated with every problem and every solution. Hence, it is necessary to gauge the consequences of a erosion either being allowed to continue through managed retreat, or re-occuring due to an unsuccessful attempt at stabilization. In principle, it is necessary to ensure that the level of risk associated with the selected solution is acceptable.

In some situations, regardless of the cause of the problem, continued bank retreat simply cannot be allowed. The frequency of problems of this type is probably fairly low, however. The "do nothing" option is then unacceptable and a management or structural solution is required. Some options carry a higher level of risk of failure than others. For example, in terms of the chance that a solution will not successfully halt bank retreat, managerial solutions are riskier than soft structures which are, in turn, riskier than hard structures. It is, therefore, important to gauge the threat posed by bank erosion in order to decide on the level of acceptable risk and, hence, appropriate type and level of response by answering the following questions:

Q2. Is the bank rate of bank retreat sufficiently severe as to lead to destabilization of the entire channel and associated dire consequences?

Q3. Is the problem likely to lead to danger to the public through the erosion of a tow-path, footpath, road or other public right of way?

Q4. Is the problem threatening significant buildings, structures or property on or behind the bank?

Q5. Is bank retreat leading to a loss of channel depth that may impede navigation?

Q6. Is bank retreat destroying irreplaceable ecosystems or riparian wildlife habitat that are not being recreated at a similar rate by fluvial and flood plain processes at some other point along the river?

If the answer to each of these questions is negative then, probably, no intervention is justified and no action or change of river and bank management is needed. This is the "do nothing" option, which can be usefully be promoted as a form of "managed bank retreat" that is consistent philosophically with modern thinking in related areas, such as coastal management.

If the answer to one or more of questions 2-6 is positive then action is justified. In this case the first option should be to consider a managerial solution.

If it is natural bank erosion that poses a serious threat to a bankside facility or path, a bank management initiative, for example through relocating the facility or path, may well be more cost effective than an attempt to interfere directly with the natural flow and channel dynamics of the fluvial system. Often, though, management through relocation or land-use change is impossible, especially in urban or highly developed catchments.

Structural intervention to deal with natural erosion must not only stabilise the bank, but also train the river into a more favourable alignment. Otherwise the erosion problem will simply be transferred to another point, adjacent to, or opposite from, the protected bank. This will trigger problems elsewhere and provoke calls for further intervention, expense and environmental disruption.

If the cause of an unacceptable problem is human activity then a change of bank management to eliminate, or at least control, the problem by dealing with the cause rather than the effect should be the preferred option. This might involve limiting public or grazing stock access to the bank, for example, creating a riparian buffer zone. Only if a managerial solution is unfeasible or too risky should recourse be made to structural intervention.

The first requirement of any solution is efficacy and to be successful it is necessary to ensure that the solution, whether managerial or structural, is matched to the problem.

3.4 Third principle: Match the solution to the problem

The basis for invoking the third principle is that experience shows that success depends entirely on selecting a solution which is relevant to the cause of the problem, covers its spatial extent and which deals adequately with all significant erosion processes, weakening factors and failure mechanisms. Having identified the cause of the problem in Section 3.2, and determined the level threat that it poses in Section 3.3, it is next instructive to answer these questions:

Q7. Is the extent of the bank erosion problem site specific, reach scale or system wide?

Q8. Is bank retreat being driven by toe scour and/or undercutting due to river currents or waves in the river?

Q9. Are there bank failures due to geotechnical instability?

Q10. Does drainage of water through, or over, the bank add to the problem?

Q11. Do processes of weakening and weathering play significant roles in promoting bank retreat by increasing bank erodibility and decreasing bank stability?

Q12. Are human activities or domestic animals responsible for accelerating erosion and, if so, what are the significant factors?

The answers to these questions form the basis for the third guiding principle: that of matching the solution to the problem. This means ensuring that: the scale of the solution encompasses the extent of the problem; the scope of any managerial solution covers all significant elements of the cause of the problem, and; the strength of any structural protection deals adequately with all significant human impacts, erosion processes, weakening factors and failure mechanisms.

Many solutions fail because they are under-scaled. An example of this design fault is a reach of intact protection works that have been out-flanked by erosion at either or both ends. Reach scale and basin-wide problems are seldom amenable to local solutions unless those solutions are part of a masterplan for training and stabilising the river. Similarly, managerial solutions must encompass a sufficient area to cover the extent of the problem. Conceivably, for system-wide problems, management changes may have to include the entire river.

Managerial solutions must also deal effectively with all significant elements of the problem. The major challenge may lie in properly identifying these elements. For example, restricting boat speeds to limit wave wash erosion may in itself be ineffective in solving a bank erosion problem if fishing pegs associated with competition angling or bank damage due to unauthorised mooring are also responsible for making the bank highly vulnerable to erosion and accelerated retreat.

This principle also holds true for structural protection. Generally, the strength of the structure must be adequate to withstand the worst possible combination of attack by flow forces and waves, in combination with weakening due to bed scour next to the structure and adverse drainage conditions. It is unreasonable to expect soft engineering structures to be a cure all and the limits to the design capabilities of various "alternative" treatments with respect to near bank velocities and scour depths must be strictly adhered to. Also, vegetative solutions need time to become established and there is a window of vulnerability after construction and prior to maturity. Hence, if the hazard of failure is great, the third guiding principle may preclude the use of a soft solution.

Most hard engineering solutions are over-designed with respect to flow and wave attack and are unlikely to be eroded by direct attack. When failures do occur, they may usually be attributed to geotechnical instability and/or seepage problems that were not identified and accounted for in the design. This underlines the need to fit the solution to the problem even when a hard solution is selected.

3.5 Fourth Principle: Balance conflicting goals in bank management

Application of the third guiding principle tends to limit the use of alternative solutions based on active bank management and soft engineering because of the greater risks associated with these approaches. This, coupled with the professionally conservative approach adopted by most river engineers, discourages application of alternative solutions and leads to a imbalance in selection towards interventions using hard structures based on their greater security. The fourth guiding principle seeks to redress this imbalance by promoting full consideration of all the issues.

Conflicts are often most stark in the use of hard solutions. Application of the fourth guiding principle means balancing the increased security of hard engineering protection against the high capital costs, low amenity value, poor aesthetics and perhaps most importantly, heavy environmental impacts. The aim must be to provide adequate bank protection where necessary but to limit the use of hard solutions to situations where there is no acceptable alternative approach. The crucial questions may be framed as:

Q13. Are the consequences of doing nothing are acceptable?

Q14. Is a managerial approach possible and, if so, are the risks associated with a non-structural solution based on active bank management be acceptable?

Q15. Does the analysis of bank problem causes, erosion processes, weakening factors and failure mechanisms indicate that treatment using a soft engineering solution is feasible and that the associated risks acceptable?

Q16. Are the high economic costs of a hard structure unwarranted by the value of the land, structures or facilities to be protected?

Q17. Are there unacceptable environmental and aesthetic impacts associated with a hard engineering structure?

If there is a positive answer to any of these questions then the fourth guiding principle indicates that a hard engineering solution should not be recommended. Conversely, negative answers to all of these questions represents a solid basis for justification of hard intervention.

The purpose of the fourth principle should be to produce a decision making system which is logical and transparent, so that decisions are not only objective and fair, but can be demonstrated to be objective and fair.

For example, for the "do nothing" option conflicts usually centre on the desire of land-owners and other people with vested interests to see action by the NRA in response to a perceived problem. The fourth principle dictates that representations be treated sympathetically and with full consideration before a decision is made not to intervene and to allow erosion to continue. The key to acceptance of this option by engineers, land-owners, special interest groups and the public rests on education. In this respect it is crucial that the NRA's policy on treating natural and non-critical bank erosion through "managed retreat" is explained and promoted effectively both through scientific papers in the professional journals and reader friendly information for non-specialists and the wider public.

In the case of soft engineering, care must be taken to balance the desire to minimise environmental impacts against the chance that the scheme will be unsuccessful. Efficacy is absolutely vital, because a soft scheme that fails reduces the credibility of the approach and wastes money, time and resources. Against this, the relatively low capital costs of soft engineering (especially if voluntary labour is available to perform the work, and repeat it as necessary) mean that it may well still be cost-effective to persist with a soft approach even if several attempts are necessary. What is crucial is the risk of unacceptable damage being done to facilities at or behind the bankline. The fourth guiding principle demands that efficacy, risk, environmental impacts and economic costs be weighed carefully when decisions are made.

3.6 Selecting the optimum solution strategy

Selection of the optimum solution depends on careful observation and interpretation of the problem coupled with balanced consideration of the impacts of intervening and the consequences of doing nothing using the four guiding principles. The objective may be summarised in the four E's:

Efficacy Economy Engineering Environment

Efficacy: means that the selected response must capable of producing the desired effect.

Economy: means that the costs of the selected response must be justified by the benefits and must represent good value for money.

Engineering: means that the engineering employed, be it soft or hard, must represented best current practice.

Environment: means that full consideration must be given to environmental issues and the impacts of either doing nothing, undertaking active bank management, or intervening through soft or hard structural protection.

4. ALTERNATIVES TO STRUCTURAL INTERVENTION

4.1 Managing the bank environment

Too often structural intervention is thought of as the first response to a bank erosion problem. Certainly, there are many situations where bank protection is clearly essential due to the severity of erosion, threat to a building or pathway, or sensitivity of riparian and flood plain ecosystems to bank destruction. This is certainly the case where the flood plain is already intensively built up and buildings encroach up to or even on to the river bank, as is the case along substantial rivers like the Thames. However, such situations probably do not constitute the majority of bank erosion problems nationally. More commonly it is questionable whether structural intervention through the stabilization of the bank by construction of either soft or hard protection is actually justified. In these cases an alternative approach to solving the problem exists through active management of the bank and its surroundings.

Management may take a number of forms, depending on the location, cause, significant processes, threat posed by the problem and level of acceptable risk of the rate of bank retreat suddenly accelerating. There are three general approaches: allowing retreat to continue; reducing the threat posed by relocating facilities or activities away from problem locations, and; eliminating or mitigating the problem by managing its cause or causes. In practice combinations and permutations of these management approaches may be used in response particular problems, in a flexible strategy that can be termed *Active Bank Management.*

4.2 The myth of the "Do Nothing" solution

Recently, it has become fashionable among geomorphologists and conservationists to recommend a "do nothing" response to many bank erosion problems. This study has shown that this term is misleading to non-specialists and its use should be discouraged.

In fact it is only possible to ascertain that no structural protection or managerial action is required after conducting a full bank assessment. As this involves a real investment of time and effort on the part of the NRA, it certainly does not equate to *doing nothing.*

If the severity of the threat currently posed by the erosion problem is small then, under the guiding principles, no structural intervention is called for and managerial solutions will involving even minimal changes to natural processes and human activities on the bank are hardly required. There is still no case of doing nothing, however.

There is always the risk of a sudden, unpredictable acceleration of erosion due to the impact of a high magnitude flow event, the crossing of a geomorphic threshold, a change in land-use or impact of a new human activity. Such an acceleration could lead to the need for a rapid change of bank management practice. Continued monitoring of the site, at an appropriate frequency of observation, is the best policy. The decision not to intervene through structural or managerial action can then be kept under review. This policy involves on-going monitoring of the problem and periodic review of the management options and it does not equate to a *doing nothing.*

Conversely, erosion at sites suffering rapid or unacceptably high rates of retreat may not be sustained for more than a short period of time. The need for monitoring and reviewing bank recession applies here also in that the case for bank management through, for example, barred access for the public may be relaxed at some time. Consequently, active management may actually tend towards "doing nothing" as conditions dictate.

It would be unfortunate if the use of a term such as "the do-nothing option" gave the impression that the NRA was not actively concerned with appropriate assessment, monitoring and treatment of all bank erosion problems, great or small. This report therefore recommends that the term "do nothing option" be replaced by one of "managed retreat" in all NRA internal policy documents and public output. Managed retreat may then be seen to be one endpoint in a continuous range of options for active bank management.

4.3 Managed retreat

Even if it is feasible practically, economically and legally, an approach based on managed retreat is still alien to most people and authorities, who see their tenure on flood plain land as being absolute and who will be unwilling to give land up to the river. This is human nature and their implacable desire to hold the bankline against the river should be recognised. However, if bank assessment and analysis indicates that holding the line at one point will actually trigger instability at some other crucial area, or may prove to be inordinately expensive economically and environmentally, then managed retreat may be a better policy for the problem. In this regard the findings of this study into erosion on navigable rivers parallel the current debate on coastal protection.

It is important that the basis for this decision be explained clearly to both the people directly affected and the wider public. Success to some extent depends on the willingness of riparian land owners and local authorities in cooperating and working with the NRA to find sensible ways forward. It is therefore necessary to win over their hearts and minds and to avoid confrontation, if at all possible.

4.4 Reducing the threat posed by bank erosion

When bank erosion does threaten to destroy a facility or disrupt some activity on or behind the bankline, the option of allowing erosion to continue but reducing or eliminating the threat that it poses by moving the facility or activity out of harms way should not be lightly dismissed. This option may even be cost effective for certain buildings and structures, depending on the costs of relocating them elsewhere compared to the cost of attempting to protect them at their present location.

However, there are serious bounds to the practicality of relocation. Land availability, economic and legal issues may well limit the application of what is otherwise a very sensible approach. In crowded flood plains such as the lower River Thames in particular, the intensity of flood plain development may well preclude relocation as a realistic option. Similarly, high land values in the developed flood plains encourage bankline stabilization because the benefits of land preservation more easily outweigh the costs. Hence, relocation is usually more realistic in the rural areas.

A nationwide limitation is that when a footpath or tow-path is threatened, even when space is available, the sensible option of moving the path back with the retreating bank may be precluded by the legal costs and procedural difficulties of making the necessary changes to the line of the public right of way.

Even if it is feasible relocation is still alien to most land owners and authorities, who will be unwilling to give way to the river. However, if bank assessment and cost-benefit analysis indicates that holding the bankline is inordinately expensive economically, unacceptable environmentally and that the alternative of removing the threat is feasible, then relocation may be a better solution to the problem.

4.5 Managing the cause of the problem

If the cause or causes of the problem can be accurately identified and are amenable to mitigation or elimination, the best managerial approach is to solve the problem by dealing with the root cause rather than with the effects. This approach contrasts with that of relocation (where the cause of the problem is untreated and retreat is allowed to continue unabated, but the threat is removed) in that there is an attempt to reduce the rate and severity of bank retreat indirectly through mitigating or eliminating the cause of the problem.

This course of action is more likely to find favour with land owners and the general public, because it is perceived as a more positive act than giving way to the river and because, in the case of human-induced problems, it involves changing the activities of the people actually causing the problem rather than of those suffering from it.

Conversely, this option will almost certainly encounter stiff opposition from the people causing the problem. Typically, private and commercial boat owners, anglers, recreational bank users, farmers and other people who's activities may be causing the erosion problem are well organised and can lobby effectively against restrictions on their activities. Also, management may well require some policing to ensure that people follow the new rules and this could potentially be a source of conflict between the NRA and some river users.

As with the relocation policy, promotion and education are absolutely vital in order to make people aware of the positive benefits of solving problems through non-structural solutions and to demonstrate why this approach is, in appropriate circumstances, better for everyone. Policing by consent and with public support should then not be a major issue.

4.6 Selection of a managerial solution

Managerial solutions will not solve every bank problem and are unrealistic in locations where there are buildings or high value facilities along the bankline. But, environmentally they are much less intrusive than structural solutions and they can be highly cost effective. It is very important that the four guiding principles be adhered to when selecting a managerial solution. This applies particularly to the third principle: matching the solution to the problem. Table 3 presents a decision support matrix to aid in the selection of managerial solutions. This can only be a guide, because in practice each problem has individual elements that cannot be generalised, and usually a flexible programme of active bank management that incorporates elements of several solution options will be called for.

4.7 Education and publicity

It is important that the basis for a decision to use active bank management in place of structural bank protection be explained clearly to both the people directly affected and the wider public. Success to some extent depends on the willingness of riparian land owners and local authorities in cooperating and working with the NRA to find sensible ways forward. It is therefore necessary to win over their hearts and minds and to avoid confrontation, if at all possible.

Public education is also crucial. The recent change of policy of the NRA on coastal defence has been promoted through positive publicity and explanation and a similar initiative is called for in the case of policies both of managed bank retreat and relocation. The signs are that public thinking would be receptive to this philosophy given the esteemed value of natural river aesthetics, recognition that it is better to work with rather than against nature and current concerns about the environmental impacts of engineered solutions.

Table 3. Selection of Appropriate Management Solutions for Bank Problems

This Table is currently being finalised in conjunction with the detailed results reported in the Project Record.

5. LEVELS OF STRUCTURAL INTERVENTION

5.1 Introduction

Where structural protection is found to be necessary a sensitive approach should be taken, which ensures that the bank is effectively stabilized using sound engineering, but which both minimises negative environmental impacts (and where possible produces environmental benefits) and represents good value for money.

The range of options and materials available to designers of bank protection has increased markedly in recent years and is set to expand further as new techniques are developed and as historical methods, forgotten in the second half of the twentieth century, are rediscovered. In this respect, bank protection technology has almost come full circle, with sixteenth century materials and structures, such as willow spilling and fascine mattresses now regarded as new and innovative approaches.

What has, however, changed since these methods were last in wide use is the public's expectation that bank protection will be successful at the first attempt. This places greater pressure on the use of alternatives to hard structures and focuses attention on the need to demonstrate the advantages of soft solution while staying within the design envelopes limiting their capabilities. This requires river scientists and engineers to assess the bank problem accurately and assign a soft solution only where bank retreat cannot be allowed and the intensity of flow attack, severity of bank and threat to buildings, other facilities or flood plain ecosystems does not merit the use of hard protection.

5.2 Soft engineering

In the context of bank protection, the term "soft engineering" covers a wide range of techniques that avoid the use of conventional rigid structures built on solid footings and using hard materials such as concrete and steel. Instead, flexible materials on deformible foundations are used to produce protection which is strong but supple.

The details of selection, design and construction are better dealt with in a design manual as they are beyond the scope of this report. A thorough review of bank protection involving vegetation has just been completed by PIANC (1993) and interested readers are directed to that publication. Hence, only the a few important wider issues that should be borne in mind when considering the use of a green, soft solution are reported here.

Soft engineering is customarily sub-divided into two categories. depending on the role played by vegetation. In the first category, 'Heavy Reinforcement Systems', vegetation is allowed or encouraged to grow on and through the structure simply to mask the artificial materials actually providing the protection and structural strength. Structural materials in heavy systems include cellular concrete blocks, gabions, textile bags, sand tubes, riprap and bitumen. Vegetation is in these cases purely cosmetic.

In the second category, 'Light Reinforcement Systems', vegetation plays an integral role in providing all or part of the protection and strength, through bio-engineering. Construction materials include cellular concrete blocks, geotextile fabrics and meshes, and reinforced turf blankets and natural vegetation such as willows, jute and coir. Biodegradable geotextiles may be used, so that after the vegetation has had time to become established and self sustaining, the protective fabric disappears.

Soft engineering must allow for uneven settlement and compaction of bank soils, adverse drainage conditions within the bank and partial failure due to direct flow attack or toe scouring. Hence, soft solutions usually make use of materials which are strong in tension as well as compression and which will can control seepage erosion by filtering water through them while retaining the soil. From the engineering viewpoint, cellular block systems where concrete elements are connected to produce a flexible mattress are attractive because the mechanical properties of the structure are predictable. Similarly, geotextiles present the ideal synthetic material for this purpose and a number of commercially patented systems of woven and extruded fabrics are available. Examples include products marketed by Netlon, Enkamat and Nicospan. The textiles are usually in the form of a continuous open fabric, mesh or web through which plants may grow. Alternatively, pockets for emergent species such as reeds may be left within the weave of a geotextile blanket.

The continued use of these geotextiles is now being called into question, however, on environmental grounds, which is ironic since they were originally developed and marketed as environmentally friendly alternatives to concrete and steel. The problem centres on the drawbacks of burying plastic or nylon in a streambank. This may now be banned in Germany because of the pollution involved. Three types of pollution are cited:

1. Pollution of the atmosphere and hydrosphere when the plastic or nylon is produced;

2. Pollution of the soil and river environment when the geotextile is buried;

3. Pollution and retardation of bank vegetation due to the take up of free nitrogen from the soil, when biodegradable geotextiles decompose.

Legislation in Europe and the USA banning the introduction of artificial geotextiles into riverine environments is a real possibility and it seems likely that Britain will follow suit in due course. Similarly, the use of bitumen as a fill material in certain systems is prohibited in Germany and the USA. These developments focus interest on "green systems" which use wholly natural materials.

Green systems work in the same way as geotextiles, but rely on plant materials for the strength as well as the aesthetics of the structure. A wide variety of species and techniques are in use, many dating from the sixteenth century. However, new and innovative approaches are being investigated. These centre on the use of natural species and materials which are found locally and which do not pollute the environment, compete with indigenous species or look out of place to river users.

There are marked differences in the approach to soft bank protection using green systems that must be recognised if use of this type of solution is to be expanded. Notable points made in the recent PIANC (1993) report are:

1. After construction soft schemes are highly vulnerable to damage by trampling or grazing. It is essential to bar access to the public and to stock. Hence, a change in bank management is implicit in the selection of a soft solution.

2. Sources of vegetation can be difficult to find. If natural areas are harvested to supply, for example, reeds or cyrex for use in bank protection elsewhere, this must be carefully managed to avoid depleting stocks at the donor site and triggering problems there;

3. If green systems are to be used routinely and on a wide scale it will be essential to propagate plants in nurseries and this will involve an investment of capital and resources;

4. There will be a temptation when local sources of plant materials are inadequate to import plants from other regions or even different countries. This involves the mixing of gene pools and should be discouraged on conservation grounds;

5. With respect to installation, timing and seasonality are crucial to success. Even the antecedent weather factor. The arrangements for contracting construction of green systems it is vital that arrangements be flexible enough to allow for delays and changes of plan due to unforeseen circumstances and that the NRA retains control over operations affect by weather, season and soil conditions. Many of the decisions normally devolved to the contractor must be made by individuals with the necessary skills in the NRA.

6. Maintenance of green systems may not be particularly more intensive than conventional protection, but it does involve different operations. Inspection, repair and routine husbandry are vital to the continued success of vegetative solutions and require an on-going commitment on the part of the NRA.

7. The selection, design, construction and maintenance of green systems demands a multi-functional approach. Specifications should be written with input and involvement by NRA staff from Flood Defence, Land Drainage, Recreation, Navigation, Fisheries, Conservation and Water Quality functions.

5.3 Mixed or 'Hybrid' structures and solutions

When the bank is suffering intense erosive attack or serious geotechnical instability, a soft solution is insufficient to stabilize the bankline. For example, if a bank is being actively undercut or toe scoured then measures are required to prevent undermining of the bank below the depth of penetration of plant roots, leading to collapse of the whole bank including the protective structure. Two possible measures would be hard protection at the bank toe, or the creation of a wet berm. Such solutions, which involve the use of hard and soft elements at different locations on the bank or extensive earth works re-profiling of the bankline, are somewhere between soft and hard solutions and may be termed "hybrid".

When hard protection is required, the lower bank and toe are the most likely areas of need. This is the case because flow attack is often concentrated there. Experience has shown that a riprap blanket in the form of a minimum stone toe is often sufficient to guard against undercutting and that once the toe is stabilized the rest of the bank may be treated with a Light Reinforcement System, as described in the previous section. Alternatives to rock would include gabion baskets or mattresses, timber cribs or piles or any type of revetment that can withstand the flow attack. Appearance and aesthetics are seldom crucial because the hard protection is submerged for the great majority of the time. Recent evidence from abroad demonstrates that the coarse substrate provided by a stone toe introduces extremely valuable habitat for invertebrates and fish.

A wet berm is a very attractive alternative to toe protection. It serves the same purpose but relies on changes in the cross-sectional geometry and bank profile to halt toe scour and undercutting. The berm protects the bank by loading the toe against mass failure and reducing the intensity of near bank velocities and damping navigation and wind waves. This is achieved at the expense of considerable earth moving to re-profile the bank and loss of flood plain land to accommodate the width of the bank and berm. Great care is needed when handling soil used in berm building and in many situations space limitations in any case preclude retirement of the bankline to allow berm building. In its favour, berm building simulates the natural healing process for an unstable bank through the accumulation of a low angle bench or spending beach at the foot of the bank. This contrasts sharply with conventional hard protection which seeks to stabilize the bank in what is usually a highly unnatural configuration. Building a wet berm is therefore consistent with the idea of working with rather than against nature and the ecological benefits and valuable habitat creation associated with this approach make it a very attractive option.

In terms of design and construction, hybrid schemes require the skills associated with both soft and hard solutions. Not only must the engineering of the toe protection be sound, but all of the requirements regarding timing, seasonality and construction management of the soft solution must also be met.

5.4 Hard engineering solutions

5.4.1 Introduction

Hard engineering is the option of last resort, to be used when other solutions based on active bank management or softer protection have been demonstrated by bank assessment to be either inadequate, or inappropriate. This may of course be quite frequently the case, and it must be accepted that in many situations there is no realistic alternative to hard protection.

Hard protection is often thought of as being *traditional*, although in fact vegetative protection pre-dates most conventional hard materials by centuries. The range of materials and techniques available is well established, although use of some approaches is increasingly limited by their adverse environmental and aesthetic impacts.

Generally, hard solutions fall into three categories: vertical walls, sloping revetments, and; groynes or spurs. Each has particular advantages and disadvantages that make it more or less desirable, depending on the situation.

5.4.2 Vertical walls

Vertical walls are conventionally constructed from driven piles made of steel, cement or wood. In the past other materials such as asbestos have been used, but this is no longer acceptable. If wood is used, the rotting of exposed timbers which are alternately wetted and dried will be a limiting factor in the design life of the structure. Also, care must be taken to prevent soil loss between the piles and a geotextile filter may be necessary to prevent this.

Exposed piling is ideal when the bank is used intensively for boat operations, mooring and manoeuvring, such as around locks and marinas. It will withstand high current velocities and wave attack, and if properly designed will be stable against severe toe scour. Submerged piling may produce adequate toe protection, but can be a serious hazard to boats.

Since the bankline is vertical, piling is useful in confined sites with restricted space for a sloping bank. Conversely, a vertical piled wall on one bank may promote erosion opposite due to wave and current reflection and care must be exercised at the limit of the wall to prevent severe erosion where the flow re-attaches to a natural, sloping bank. This usually requires some form of transitional protection using a revetment.

Vertical walls provide little or no valuable habitat. Their poor aesthetics also count heavily against them to the extent that local planning permission may well be denied in rural areas.

5.4.3 Sloping Revetments

Revetments are probably the most popular form of hard protection currently in use world wide. They may be constructed from a wide variety of materials including rock, rubble, concrete blocks of various shapes, filled textile bags, and gabion baskets or mattresses. The choice of material is governed by local conditions and particularly by their availability, as transport costs are high.

Design guidance for revetments is well developed in both fluvial and wave attack environments and whatever the material used the probability of failure will be small provided that design criteria are followed rigourously. Experience shows that where revetments do fail this can usually be attributed to: excessive and unpredicted toe scour next to the revetment, flanking due to excessive bank erosion at either or both ends of the revetment, or geotechnical instability associated with deep seated failure or adverse drainage in the bank. To guard against these outcomes, it is important to load the toe of the revetment with a launching apron to prevent undercutting, to ensure that the revetment is sufficiently long to cover the entire reach of eroding bank and to take great care over the design of seepage filters within the revetment to retain soil but allow free drainage.

Stone is the preferred material for most revetments. If the available stone is too small to withstand flow and wave attack in a loose blanket, it can still be used to fill wire gabion baskets or mattresses. Often though, the extra cost of making gabions is unjustified unless space is limited and it is desired to build the revetment at a very steep slope. Other materials such as concrete and bag work can also be used at steep angles. As a natural material rock has much to commend it over artificial alternatives, although boulders of the size used in revetment are not a natural feature of lowland river banks, and hence unvegetated riprap and gabion revetments can appear out of place.

Increasingly, revetment is designed with vegetation as an integral component either for cosmetic or structural reasons. The appearance of almost any revetment can be improved using vegetation. Volunteer species tend not to be desirable and a pro-active approach in which seeded soil or living plants are introduced to the revetment are increasingly popular. In this respect, light revetments can almost be considered as a type of soft solution.

Problems do exist with vegetated revetment, however, and these must be borne in mind. Vegetation obscures the structure making inspection much more difficult and the stems of woody species may breach the protective armour either through mechanical disturbance or through generating local turbulence during high flows. Usually, it is wise to limit vegetation on revetments to grasses, reeds and shrubs rather than trees, and pollarding, coppicing or removal of woody species is required. In this respect, the inspection and maintenance commitments for vegetated revetments are much greater than for unvegetated ones.

5.4.4 Groynes and Spurs

Groynes and spurs work differently to longitudinal bank walls and revetments in that they attempt to protect the bank by reducing near bank velocities and wave intensities rather than by armouring the bank against those forces. While this approach has proved very effective on large, navigable rivers such as the Rhine and the Mississippi, it applicability to smaller navigable waterways in Britain is very limited. This is the case because the intensity of flow attack in cases does not justify deflection by groynes or spurs and because such structures extending into the river could themselves pose a navigation hazard. On the other hand, flow deflectors create valuable slack water habitats between them, especially if designed with notches to allow limited through flow. In this respect, they can provide environmental benefits.

Innovative structures such as Iowa vanes or bendway weirs being developed in the USA could potentially have some useful applications at the outer bank in bends, where the current attack is strong, but these devises need further development before they could be accepted for routine rather than research and development usage.

5.5 Selection of a Structural Solution

The selection of a structural solution must be justified by the findings of the bank assessment. Once a decision to intervene directly has been taken, then steps must be taken to ensure that the solution selected is appropriate to the problem and can deal effectively with all of the destabilizing forces and processes responsible for for bank retreat. Table 4 presents a decision support matrix for selection of a structural solution.

Table 4. Selection of Appropriate Structural Solutions for Bank Problems

This Table is currently being finalised in conjunction with the detailed results reported in the Project Record.

There exists great potential for softening the impact of hard solutions using sloping revetments, through the use of natural materials and the thoughtful use of cosmetic vegetation. This softening does not come without a price, however, and the added costs of inspection and maintenance of vegetated structures must be taken into account when a solution is selected.

6. CONCLUSIONS AND RECOMMENDATIONS

This section is best written in the light of comment and advice from the NRA reviewers regarding the most important findings and recommendations in the R & D Report. Given the current discussion regarding the role of this R&D Report, it would be premature to try and frame the full conclusions and recommendations at the moment. The correct way forward will become clear following debate and discussion within the NRA and between interested parties. Hence, only outline conclusions are listed in this draft report.

1. The research conducted in this study has demonstrated that bank erosion is widespread on navigable rivers, but that it is not always attributable to boat wash or boat operations. Some erosion is a component of the natural processes operating in the fluvial system, and a great deal is either caused or accelerated by human activities such as angling, use of footpaths and uncontrolled access by farm stock.

2. Bank erosion does not always constitute a serious problem that merits treatment through structural intervention. However the decision whether or not to protect the bank must be based on the best evidence available. This highlights the importance of using careful observation of bank form and process to establish the cause of the problem, together with guidance on the selection of an appropriate solution for different causes and types of problem.

3. If a decision is made to allow erosion to continue, this does not equate to doing nothing. Hence, it is recommended that the term "do nothing solution" be dropped in favour of the term "managed retreat".

4. Where erosion cannot be allowed to continue, the possibility for a managerial solution should explored before recourse is made to structural protection.

5. Where structural protection is required, soft and hybrid solutions are preferred over hard engineering. However, the widespread adoption of soft solutions involving vegetation will demand major changes of approach by the NRA particularly in the areas of contracting and construction management. The use of vegetative protection is likely to be limited by the availability of suitable plants in the near to medium future.

6. In order to support decision making that is both scientific and defensible to the public, it is vital that logical and coherent policies on bank erosion be decided for each region within a national framework.

7. The selection of an appropriate response to a bank erosion problem can be aided by consideration of four guiding principles:

    * Identify the cause of the bank erosion problem. If it is purely due to natural erosion as part of the fluvial system then, if possible, allow it to continue. Avoid intervention unless bankline retreat is absolutely unacceptable;

    * Where retreat cannot be allowed, and especially if the cause is human activity, seek a solution through active bank management, and only intervene with structural protection when this alternative approach is not acceptable;

    * When active management or structural intervention are justified, match the scope, strength and length of bank covered by the solution to the cause, severity and extent of the problem. Active bank management and soft engineering, although desirable, are not appropriate for locations of intensive bank attack.

Every unsuccessful managerial or soft solution detracts from the credibility of the approach and damages the image of alternative solutions.

* When reacting to a bank erosion problem and deciding on a course of action, bear in mind the responsibility to balance conflicting goals in river management to achieve the optimum solution in terms of the four E's:

  Efficacy, Economy, Engineering and the Environment.

7. REFERENCES AND FURTHER READING

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APPENDIX A **Bank Assessment Record Sheets for Field Appraisal of Bank Erosion Problem Sites.**

BANK ASSESSMENT RECORD SHEET

Developed by Colin R. Thorne
for the National Rivers Authority

SECTION 1 - SCOPE AND PURPOSE

Brief Statement of Bank Erosion Problem:-

Purpose of Bank Assessment:-

Logistics of Field Assessment Visit:-

RIVER NAME LOCATION DATE

PROJECT STUDY REACH From To

SHEET COMPLETED BY

RIVER STAGE TIME: START TIME: FINISH

General Notes and Comments on Bank Assessment Visit:-

SECTION 2 - CHANNEL SKETCH MAP

Map Symbols

Study reach limits	u/s limit d/s limit	North point	N	Cut bank		Photo point	P1
Cross-section	A——A'	flow direction		exposed island/bar		Sediment sampling point	S2
Bank profile	B3	impinging flow		structure		Significant vegetation	

Representative Cross-section(s): Show locations on Sketch Map

A.

B.

C.

D.

SECTION 3 - BANK SURVEY

PART 1: BANK CHARACTERISTICS

Type
Noncohesive ☐
Cohesive ☐
Composite ☐
Layered ☐
Even Layers ☐
Thick+thin layers ☐
Number of layers ___

Protection Status
Unprotected ☐
Hard protection ☐
Soft protection ☐
Mixed protection ☐

Bank Materials
Silt/clay ☐
Sand/silt/clay ☐
Sand/silt ☐
Sand ☐
Sand/gravel ☐
Gravel ☐
Gravel/cobbles ☐
Cobbles ☐
Cobbles/boulders ☐
Boulders/bedrock ☐

Layer Thickness
Material 1 (m) ___
Material 2 (m) ___
Material 3 (m) ___
Material 4 (m) ___

Ave. Bank Height
Average height (m) ___

Ave. Bank Slope
Average angle (o) ___

Bank Profile Shape
(see sketches in manual) ☐

Tension Cracks
None ☐
Occasional ☐
Frequent ☐

Crack Depth
Proportion of bank height ___

Distribution and Description of Bank Materials in Bank Profile

	Material Type 1	Material Type 2	Material Type 3	Material Type 4
Toe	☐	☐	☐	☐
Mid-Bank	☐	☐	☐	☐
Upper Bank	☐	☐	☐	☐
Whole Bank	☐	☐	☐	☐
D50 (mm)	___	___	___	___
sorting coefficient	___	___	___	___ (sorting coef.)

Notes and Comments on Bank Characteristics:-

PART 2: BANK STRUCTURES

Structure Type
None ☐
Revetment ☐
Vertical wall ☐
Sloping wall ☐
Other (Specify) ☐

Materials
Rock ☐
Concrete ☐
Brick ☐
Timber ☐
Steel ☐
Other (Specify) ☐

Structure Data
Date Constructed ___
Length (m) ___
Height (m) ___
Side Slope (o) ___
Orientation ___

Structure Condition
Acceptable ☐
Marginal ☐
Unacceptable ☐

Problems Observed
None ☐
Flow Erosion of the structure ☐
Flow scour next to the structure ☐
Seepage failures in the structure ☐
Slumping of the structure ☐

Notes and Comments on Bank Structures:-

PART 3: BANK-FACE VEGETATION

Vegetation
None/fallow ☐
Artificially cleared ☐
Grass and flora ☐
Reeds and sedges ☐
Shrubs ☐
Saplings ☐
Trees ☐

Orientation
Angle of leaning (o) ___

Tree Types
None ☐
Deciduous ☐
Coniferous ☐
Mixed ☐
Tree species (if known) ___

Density + Spacing
None ☐
Sparse/clumps ☐
dense/clumps ☐
Sparce/continuous ☐
Dense/continuous ☐

Roots
Normal ☐
Exposed ☐
Adventitious ☐

Location
Whole bank ☐
Upper bank ☐
Mid-bank ☐
Lower bank ☐

Diversity
Mono-stand ☐
Mixed stand ☐
Climax-vegetation ☐

Health
Healthy ☐
Fair ☐
Poor ☐
Dead ☐

Age
Imature ☐
Mature ☐
Old ☐

Height
Short ☐
Medium ☐
Tall ☐
Height (m) ___

Lateral Extent
Wide belt ☐
Narrow belt ☐
Single row ☐

Notes and Comments:-

SECTION 4 - BANK PROBLEMS

PART 4: BANK EROSION

Erosion Location
- General [ ]
- Outside Meander [ ]
- Inside Meander [ ]
- Opposite a bar [ ]
- Behind a bar [ ]
- Opposite a structure [ ]
- Adjacent to structure [ ]
- Dstream of structure [ ]
- Ustream of structure [ ]
- Other (write in) [ ]

Present Status
- Intact [ ]
- Eroding:dormant [ ]
- Eroding:active [ ]
- Advancing:dormant [ ]
- Advancing:active [ ]

Rate of Retreat m/yr (if applicable and known) ___

Rate of Advance m/yr (if applicable and known) ___

Interpretative Observations

Severity of Erosion
- *Insignificant* [ ]
- *Mild* [ ]
- *Significant* [ ]
- *Serious* [ ]
- *Catastrophic* [ ]

Extent of Erosion
- *None* [ ]
- *Local* [ ]
- *General* [ ]
- *Reach Scale* [ ]
- *System Wide* [ ]

Processes
- *Parallel flow* [ ]
- *Impinging flow* [ ]
- *Piping* [ ]
- *Freeze/thaw* [ ]
- *Sheet erosion* [ ]
- *Rilling + gullying* [ ]
- *Wind waves* [ ]
- *Vessel waves* [ ]
- *Other vessel forces* [ ]
- *Other (write in)* [ ]

Distribution of Each Process on Bank

Process 1		***Process 2***	
Toe (undercut)	[ ]	*Toe (undercut)*	[ ]
Lower bank	[ ]	*Lower bank*	[ ]
Upper bank	[ ]	*Upper bank*	[ ]
Whole bank	[ ]	*Whole bank*	[ ]
Process 3		***Process 4***	
Toe (undercut)	[ ]	*Toe (undercut)*	[ ]
Lower bank	[ ]	*Lower bank*	[ ]
Upper bank	[ ]	*Upper bank*	[ ]
Whole bank	[ ]	*Whole bank*	[ ]

Level of Confidence in answers (Circle one)
0 10 20 30 40 50 60 70 80 90 100 %

Notes and Comments on Bank Erosion:-

PART 5: BANK GEOTECH FAILURES

Failure Location
- General [ ]
- Outside Meander [ ]
- Inside Meander [ ]
- Opposite a bar [ ]
- Behind a bar [ ]
- Opposite a structure [ ]
- Adjacent to structure [ ]
- Dstream of structure [ ]
- Ustream of structure [ ]
- Other (write in) [ ]

Present Status
- Stable [ ]
- Unreliable [ ]
- Unstable:dormant [ ]
- Unstable:active [ ]

Failure Scars+Blocks
- None [ ]
- Old [ ]
- Recent [ ]
- Fresh [ ]
- Contemporary [ ]

Interpretative Observations

Instability:Severity
- *Insignificant* [ ]
- *Mild* [ ]
- *Significant* [ ]
- *Serious* [ ]
- *Catastrophic* [ ]

Instability: Extent
- *None* [ ]
- *Local* [ ]
- *General* [ ]
- *Reach Scale* [ ]
- *System Wide* [ ]

Failure Mode
- *Soil/rock fall* [ ]
- *Shallow slide* [ ]
- *Rotational slip* [ ]
- *Slab-type block* [ ]
- *Cantilever failure* [ ]
- *Pop-out failure* [ ]
- *Piping failure* [ ]
- *Dry granular flow* [ ]
- *Wet earth flow* [ ]
- *Other (write in)* [ ]

Distribution of Each Mode on Bank

Mode 1		***Mode 2***	
Toe	[ ]	*Toe*	[ ]
Lower bank	[ ]	*Lower bank*	[ ]
Upper bank	[ ]	*Upper bank*	[ ]
Whole bank	[ ]	*Whole bank*	[ ]
Mode 3		***Mode 4***	
Toe	[ ]	*Toe*	[ ]
Lower bank	[ ]	*Lower bank*	[ ]
Upper bank	[ ]	*Upper bank*	[ ]
Whole bank	[ ]	*Whole bank*	[ ]

Level of Confidence in answers (Circle one)
0 10 20 30 40 50 60 70 80 90 100 %

Notes and Comments on Bank Geotech Failures:-

SECTION 5 - BANK TOE CONDITION

PART 6: BANK TOE SEDIMENT ACCUMULATION

Stored Bank Debris
- None [ ]
- Individual grains [ ]
- Aggregates+crumbs [ ]
- Root-bound clumps [ ]
- Small soil blocks [ ]
- Medium soil blocks [ ]
- Large soil blocks [ ]
- Cobbles/boulders [ ]
- Boulders [ ]

Vegetation
- None/fallow [ ]
- Artificially cleared [ ]
- Grass and flora [ ]
- Reeds and sedges [ ]
- Shrubs [ ]
- Saplings [ ]
- Trees [ ]

Age
- Immature [ ]
- Mature [ ]
- Old [ ]
- Age in Years [ ]

Tree species (if known) ___

Health
- Healthy [ ]
- Unhealthy [ ]
- Dead [ ]

Roots
- Normal [ ]
- Adventitious [ ]
- Exposed [ ]

Interpretative Observations

Toe Bank Profile
- *Planar* [ ]
- *Concave upward* [ ]
- *Convex upward* [ ]

Present Debris Storage
- *No bank debris* [ ]
- *Little bank debris* [ ]
- *Some bank debris* [ ]
- *Lots of bank debris* [ ]

Sediment Balance
- *Accumulating* [ ]
- *Steady State* [ ]
- *Undercutting* [ ]
- *Unknown* [ ]

Level of Confidence in answers (Circle one)
0 10 20 30 40 50 60 70 80 90 100 %

Notes and Comments:-

Detailed Bank Map and Profile Sketches

Map and Profile Symbols

Bank Top Edge	Failed debris	Engineered Structure
Bank Toe	Attached bar	Significant vegetation
Water's Edge	Undercutting	Vegetation Limit

Bankline Map

Typical Bank Profiles (Show Locations on Bankline Map)

a

b

c

d

Bank Assessment Summary Sheet

Observed Condition of Bank including any Existing Protection

Location, Extent, and Severity of Erosion Threat

Significant Erosion Processes and Failure Mechanisms

Cause(s) of Problem

Suggested Action and Justification

(Managed Retreat/Active Bank Management, Soft/Hard/Hybrid Structural Protection)