A PROTOTYPE DECISION SUPPORT SYSTEM FOR STREAMBANK REHABILITATION

by

KILAAN CHRISTOPHER SCHOEMAN

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ABSTRACT

The condition of a stream is often judged by the state of its banks. This, the lack of adequate advice for streambank rehabilitation, and the drive by legislation, particularly the National Water Act, 1998 (RSA Act no. 36 of 1998) and the National Environmental Management Act, 1998 (RSA Act no. 107 of 1998), to restore South African riparian areas, created a need for more information into such systems. Identifying a gap in what we know about rehabilitating degraded streambanks led to the development of a decision support system for the selection of streambank rehabilitation techniques. The Streambank Rehabilitation Decision Support System, or SR-DSS, aims to provide riparian managers with advice on choice of technique at degraded streambank locations along a river system. Techniques were sought from the scientific literature and organised to recommend appropriate techniques for combating certain erosive processes.

Rutherford *et al.* (1999) conclude that placing priority on sites of lower importance may be an inefficient manner of spending the resources at hand. Foreseeing this likelihood, a priority setting system was developed and based on the principles of Rutherfurd *et al.* (1999). These principles aim to prioritise human interests without compromising ecological interests. Along a given stream, the areas of degradation that compromise property will nearly always have the highest priority. Once these have been addressed, sites of ecological value are taken into consideration followed by sites that require substantial effort to restore. It is argued that sites taking substantial effort to restore have the least to 'loose' should they degrade further.

To enable the use of these principles a site scoring system was developed, so that sites could be prioritised. This was based on the value and threat rating tables developed by Heron *et al.* (1999). It was soon realised that a framework was needed within which the above could be set. For this purpose, Kapitzke's (1999) planning and design procedure was adapted to form an eleven-step framework which would guide the rehabilitation venture from priority setting, to the treatment outcome. The rehabilitation approach was tested in the case of the Foxhill Spruit. The small size of the catchment allowed the different segments of the approach (framework, priority setting model, field assessment sheet and SR-DSS) to be tested in real world conditions. The approach was found to have a number of strengths. The framework brought to the attention of the user, the dominant forces at play at each site, and was useful in determining the recommendation given by SR-DSS. The priority setting model allowed sites to be arranged in order of priority, that, according to Rutherfurd *et al.* (1999), would be the most efficient in terms of ecological value maintained, and resources saved. The field assessment sheet was consistent in rating the degree of intervention required, and in each case directed the user to the appropriate sections in SR-DSS. SR-DSS recommended appropriate techniques that would match the erosive forces occurring at each site. Comparing the technique chosen by SR-DSS

to techniques that may have been recommended instead substantiated this finding. The techniques chosen by SR-DSS were found to be superior. This approach considers all aspects of sound streambank rehabilitation and may be used to gain advice on small streams in South Africa.

PREFACE

The research described in this mini-dissertation was carried out at the Centre for Environment and Development, University of Natal, Pietermaritzburg, under the supervision of Dr Nevil Quinn.

This mini-dissertation represents the original work of the author and has not otherwise been submitted in any form for any degree or diploma at any university. Where use has been made of the work of others it is duly acknowledged in the text.

Kilaan Christopher Schoeman

Dr Nevil Quinn

FOREWORD

The rapid increase in world populations and unparalleled ecological destruction will significantly affect the future of the human species (Cairns, 1995a; Clarke, 1991). It follows that we are compelled to take one of three choices: 1) maintain the present rate of unsustainable resource use, which will undoubtedly end in eventual collapse, 2) institute a "no-net-ecosystem-loss" policy whereby everything that is lost, or destroyed, is replaced in kind, and 3) extend the "no-net-ecosystem-loss" policy such that the rate of ecosystem repair exceeds that rate of ecosystem destruction, so that ecosystem services do not diminish spontaneously as global populations reach the 10 billion mark projected for the year 2025 (Cairns, 1995a; Clarke, 1991; http://www.enn.com, 20/05/2000). It seems most likely, that should populations continue to grow unabated (Stephen Hawkins estimates, humans will stand shoulder to shoulder by the year 2600 at the present growth rate), ecologically repaired ecosystems such as rehabilitated riparian areas, will not survive due to increased anthropogenic-based pressures. Even so, as Cairns (1995a) points out, even temporary ecosystem repair would be of benefit to the environment in general, for the services they perform. If sustainability is to be achieved, then both stabilising the human population and effectively rehabilitating damaged ecosystems makes sense (Cairns, 1995a; Clarke, 1991; http://www.enn.com, 20/05/2000; Hullar, 1999; Strong, 1990; Toepfer, 1999). This work focuses on the latter.

It is well established that riparian areas are the critical buffer zones between land and water (Cairns, 1995a; Clarke, 1991; LWRRDC, 1998). Therefore, they play an important role in the life cycle of many animals and plants. The better soils and more moist conditions are usually reflected in the vegetation occurring there. However, their high potential for production has often jeopardised their existence as fully functioning systems, and they are often targeted for use in intensive cropping and other forms of development. Formal engineering techniques, pollution, over-abstraction and unsympathetic environmental management have contributed heavily to the destruction of many riparian areas. In an attempt to check this destruction, there has been an emergence, especially in the last decade, of a series of river rehabilitation projects aimed at the enhancement of degraded river habitats and the improvement of a wider riparian landscape (LWRRDC, 1998). Part of the objective of this document therefore, is to justify the spending of money and effort on the rehabilitation of riparian systems. The question is why rehabilitate? The answer to this question will be attempted (in Chapter 1) by showing the benefits received from a fully functioning river system and how it can result in a good economic and environmental investment. The key challenge therefore is to extend what Cairns (1995a) and Clarke (1991) call, the "no-net-ecosystem-loss" policy such that the rate of ecosystem repair exceeds that rate of ecosystem destruction. For this purpose, an effective process whereby a riparian ecosystem can be rehabilitated, needs to be sought. It is in this undertaking, where the other part of the objective of the document lies. Rehabilitation techniques presented in the world's literature will be categorised and linked to a decision support system. The process is dubbed Streambank Rehabilitation Decision Support System or SR-DSS and is intended to assist in the management of riparian areas. It will consist of a larger framework in which priorities will be set between sites or even catchments. The decision support system may also be used on its own where the user has already chosen the site to be rehabilitated and priorities do not need to be set. It is hoped that the product of this research will form a powerful decision making tool, and will increase the success rate of streambank rehabilitation projects.

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CHAPTER 1

Introduction

1.1 The functions and values of riparian systems

The current state of South African streams and rivers has forced the government to play a definitive role in the interaction between riparian areas and man. Evidence of this may be seen in the recent development of the National Environmental Management Act, 1998 (RSA Act number 107 of 1998), and more specifically, the National Water Act, 1998 (RSA Act number 36 of 1998). The importance of riparian areas to the natural environment has therefore been recognised and is reflected in the legislation.

Riparian areas are usually highly fertile, attributed to their position lower in the landscape, and often retain water over a longer period. This makes them highly sought after for cropland. The variation in habitats and food types, proximity to water, their macroclimate, and the ability of such areas to provide refuge attracts a wide variety of species. Many of these are endemic, contributing to the life cycles of other organisms. However, riparian areas are not only important from an ecosystem perspective. They have also been recognised to perform several social functions. Some of these and their ecological functions have been discussed below.

(i) Water quality enhancement

Each year, millions of Rand are spent treating water to make it fit for human consumption (Clark *et al.,*1985). As contaminants move off the land and into streams, the cost of treating municipal water supplies increases. In the USA, the treatment of water costs every individual US$ 3 to US$ 5 per month (Welsch, 1991). This means that in a city of one million residents, the sums spent could be as much as $60 million per annum. These costs would be greatly reduced by properly functioning riparian systems (Palone & Todd, 1997). A positive sentiment is reflected in the attitudes of Americans on this subject. A survey conducted during the 1990's found that individuals were willing to pay US$ 275 to US$ 366 per household, per year on environmental aspects that would improve the quality of their river water to a swimmable level (Carson & Mitchell, 1993).

Pollutants cause problems and expense for industry. Contaminated water has long been known to cause electric power plants to operate less efficiently (Klapproth, 1999). Suspended sediments, cost steam electric power plants and other water cooled facilities an estimated US$ 24 million annually in the USA (Schlosser & Karr, 1981; Ribaudo, 1986) and the sedimentation of lakes and reservoirs costs US$ 1,1 billion per year (Ribaudo, 1986). Furthermore, pesticides that are transferred directly from fields to rivers can be accumulated in food webs. Fully functioning riparian areas, of which streambanks are an essential component, function as filters for nutrients, pollutants and catchment erosion (Veneman, 1994; Bren *et al.,* 1997; Klapproth, 1999). Their filtering efficiency may be well above 80% (Gilliam *et al.,* 1986). Properly structured land-water buffer zones allow not only the retention of nutrients and pesticides transported to a river, but may also hasten nutrient spiraling through optimisation of in-stream primary productivity (Ellwood *et al.,* 1983) and thus increase the self-purification ability of a river.

By creating areas of intermediate complexity in small rivers (buffers), we can expect on one hand, the improvement of habitat variability, organic matter supply and retention, and on the other, the acceleration of nutrient spiraling and energy transfer to the top trophic levels. All these processes will result in an increase in productivity, improvement of self-purification, and the consequent reduction of down-stream eutrophication (Veneman, 1994). This has potentially high value in that large sums of money may be saved on the improvement the quality of water provided for domestic purposes.

(ii) Provide areas for recreation

In recent years the use of riparian areas for recreation has increased worldwide (Pigram, 1983; Pawelko *et al.,* 1995). This was substantiated in a study conducted in Alabama, USA, where nearly 77% of people surveyed, felt that it was important to have natural areas close to where they live and work (Palone & Todd, 1997).

Economic benefits from recreational use of riparian areas are not to be underestimated. In the state of Virginia USA, alone, fishing contributed US$ 821 million to the state's economy and US$ 37,8 billion is spent nation-wide annually (U.S. Fish and Wildlife Service and U.S. Bureau of the Census, 1996). In 1988, white water rafters in western Maryland, USA, contributed US$ 1,2 million to the local economy (Gitelson & Gaefe, 1990). Furthermore, Emerson (1996) cites the value of riparian areas culturally. The pollution and degradation of riparian areas can quickly reduce the potential for recreational and cultural use especially where sites have reduced appeal due to, for instance, degraded streambanks.

(iii) Deliver aesthetically pleasing landscapes

The importance of an aesthetically pleasing terrain and recreational value is often under-estimated. Litton (1977), suggests that people are drawn to river areas because of their visibility, water movement, reflections and colour, and their consequent contrast to the adjacent earth surface. Kuska (1977), also suggested other features, such as rapids, can increase the appeal of streams. On the other hand, streams that are heavily impacted upon (e.g. degraded streambanks, presence of litter, man-made features, or evidence of poor water quality) can distract from aesthetic appeal (Leopold, 1969; Hoover *et al.*, 1985). The importance of aesthetically pleasing terrain is especially important to the Japanese, who's government spent US$ 200 million to provide a flow in the waterways of Tokyo for recreational and ecological benefit (Gippel & Fukutome, 1998). Authorities are coming under increasing pressure to restore riparian areas. In Japan the response has been rapid and earnest, with the number of sites being rehabilitated surpassing 1500 (Gippel & Fukutome, 1998). The result is that people can enjoy a higher quality of life in a healthier and safer environment.

(iv) Maintain biodiversity

Natural stream habitats, which include surrounding riparian zones as well as in-stream environments, are varied and diverse and as a result, sustain an abundance of fauna and flora. Organisms have correspondingly evolved to exploit both the spatial and temporal variation found within and adjacent to the stream (Sullivan *et al.*, 1987). They therefore form areas of high conservation value. In channeled stream reaches, this complexity has been compromised, reducing or eliminating the stream's ability to support and maintain a healthy ecosystem. Major impacts occur from the loss of substrate; removal of snags[1], detritus, and debris; loss of in-stream and stream-side vegetation; disruption of the run-riffle-pool sequence (Newbury *et al.*, 1998); loss of stream length; increased gradient and velocity; alteration of the physicochemical regime; and the reduction of allochthonous inputs (Simpson *et al.*, 1982). Properly designed rock riffles or rapids may be constructed in naturally uniform and channeled streams to restore stream stability and to re-establish lost fish and benthic habitats. For example, the rehabilitation of Oulette Creek, in British Columbia, catalysed the immediate recruitment by fish (of up to 540% increase) from upstream reaches and a shift in species and/or age class structure (Newbury *et al.*, 1998).

(v) Flood alleviation

Damage caused by flooding, amount to millions of Rand lost yearly. Annual flood damages in the USA amount to more than US$ 887 million (Ribaudo, 1986). Healthy riparian systems reduce flood damage by decreasing the velocity at which storm waters move through the flood plain, reducing the water's erosive potential, and capturing materials carried by the water (Gregory *et al.*, 1991). By decreasing the velocity of the water, it is allowed to soak into the soil, meaning more stream flow captured and retained higher in the watershed.

[1] Large woody debris such as logs and branches that fall into rivers.

(vi) Erosion control

Functioning riparian zones reduce the amount of sediment transported to a river. It is well documented that rehabilitation techniques improving the condition of streambanks alleviate the erosion of soil (Gilliam *et al.,* 1986; Veneman, 1994; Bren *et al.,* 1997; Klapproth, 1999). Newbury *et al.* (1998) cited the Waukegan Park district, Illinois, USA, as an example, which implemented a streambank rehabilitation program to combat storm water runoff which was causing severe bank erosion. The Illinois State Water Survey was authorised to develop streambank stabilisation practices to protect city infrastructure and restore the recreational and environmental benefits of park lands. Biotechnical bank stabilisation was chosen, where riparian vegetation was combined with structural stabilisation. The techniques implemented were bank covers and interlocking concrete jacks which were designed to resist high velocity run-off while increasing riparian habitat for stream fisheries. Additional benefits included an increase in water quality and a reduction in the siltation of reservoirs and lakes.

(vii) Navigation

Some countries rely heavily on channels and rivers for transportation. The sedimentation of these waterways reduces their capacity to handle commercial ships and dredging is often required to keep them open. Harbours are also prone to sedimentation. Baltimore Harbour, USA, spends US$10 to US$11,5 million annually to dredge sediments (Palone & Todd, 1997), while Durban Harbour, South Africa, spends R 10 million annually (Dorian Bills 2000 *pers. comm.*) for in-port dredging. This amount is said to rise to R 40 million when polluted water enters the port via the river (Dorian Bills 2000 *pers. comm.*). Considerable cost savings could be achieved simply by maintaining the integrity of the river systems feeding into the habour.

Ironically, the important role riparian areas play has been a significant factor in their degradation, caused by the high interaction between riparian areas and humans. The following section will explore this deeper.

1.2 Degradation of streambanks and riparian zones

Problems related to degraded streambanks are varied and diverse, and the solutions are even more so. Although fires, severe frosts, cyclones, and major floods can all have negative impacts on streambanks, human impact since European settlement, has resulted in the greatest force producing change and degradation to riparian areas (LWRRDC, 1999a). Degradation has resulted largely from wide-scale removal of riparian vegetation, although cultivation, industry, stock and exotic species contribute to this condition considerably. These impacts function to degrade streambanks and riparian areas in general in the following manner (LWRRDC, 1999b):

- desnagging resulting from a need to free the corridor of blockages, may eliminate important habitat for aquatic organisms, disrupting the aquatic ecosystem

- removal of vegetation allows more light to the surface giving potential problem species, such as algae and weeds a better chance, while plants that protect the bank and give it stability have less chance for survival
- removal of riparian vegetation encourages the destabilisation of streambanks, increasing channel width, channel incision and gully erosion; while allowing the uncontrolled flow of water downstream, offering no resistance, ultimately contributing to increased flooding and erosion of lowlands
- cultivation on the banks of many streams, not only destabilises them, but increases the delivery of sediments and nutrients to streams
- alteration of water regimes (e.g. dams and weirs) has affected aquatic ecosystems and the capacity of channels to carry flow, directly affecting the stability of streambanks
- channel straightening and mining of sand and gravel has often led to channel incision and head cutting, influencing bank height and shape leading to increased erosion rates
- uncontrolled stock access has in many cases led to trampling and overgrazing of vegetation, and breakdown of the soil structure and ultimately bank collapse
- alteration of fire regimes and invasion by exotic species has further contributed to degrading river banks by offsetting the balance between the forces that have shaped the bank to its natural state.

1.3 Problems with degraded streambanks

The problems created by degraded riverbanks can be multi-faceted and can become increasingly more complicated with time. Each problem has a growing number of causes and/or outcomes that are all interrelated (de Waal *et al.*, 2000). The cause or outcome of one problem can weaken or strengthen that of another, and obviously the solution to one problem depends on the solution to another. Uncertainty arises mostly from a lack of scientific knowledge about cause and effect relations. This means that the effects of certain measures are not known before they are put into practice. In essence, as time proceeds, problems become more complex and only if rehabilitation is able to solve the problems of the river bank, can the natural functions of that river be restored (de Waal *et al.*, 2000). The implication of this on the streambank rehabilitation effort is that uncertainty exists over the success of the approach until it is tested in the field and scientifically evaluated. Only once this happens can the success be measured. This will be dealt with in more detail in Chapter 2.

1.4 The extent of streambank degradation around the world and in South Africa

Globally, some 25,34 billion tonnes of soil are removed by erosion annually (LWRRDC, 1999a), a large part of which is contributed by eroding and collapsed streambanks. In Australia it has been estimated that since European settlement, the ecological state of streambanks has steadily declined. For example, around 14 billion tonnes of soil are removed by sheet and rill erosion annually - about 19% of global figures (a large amount of this is actually removed from streambanks). Of 27 Victorian river basins, only 44% have more than half of the stream length in an excellent or good environmental category and, soil and water degradation costs Australia more than AU$ 1,4 billion (R5.6 billion) annually (Mitchell, 1990).

The situation is similar in South Africa. In the State of the Environment Report, South Africa (1999), it has been reported that:

- 25% of terrestrial habitats have been transformed for cultivation of crops, forestry, industry and human settlements (this figure is likely to be much higher for riparian areas)
- 5% of terrestrial habitats have been degraded (again, this figure is likely to be higher for riparian areas)
- 8% of riparian habitats are heavily infested with alien vegetation
- there is major concern over sedimentation of estuaries, reduced flooding frequency, and poor water quality
- soil is being lost 8 times faster than it is being generated

It seems therefore, that the state of the world's, and South Africa's, streambanks are heavily degraded, and getting worse every year. The need for rehabilitation initiatives are becoming ever more necessary. Considering the resources available to remedy the problems, it is important to have a very high success rate. However, what does streambank rehabilitation imply, and is it achievable? This will be the focus of the following sections.

1.5 The streambank rehabilitation movement

Great interest has been shown in riverbank rehabilitation and river rehabilitation in general, in recent years, especially from first world countries such as Australia, the UK, and the USA. Most of the literature available, is sourced from those countries. The key guidelines that have been produced to date include those displayed in Table 1.

These documents deal with the restoration effort and attempt to help people rehabilitate rivers. As can be seen, there is a wide variety of fields of interest displayed in these documents. These range from a broad perspective or catchment approach, to dealing with specific problems such as streambank stability. There is still a need, however, to guide the user through the rehabilitation process, which is the essence of what is being attempted by this research.

Table 1: Some key rehabilitation guidelines that have been produced to date.

Title	Author(s)
Environmental Restoration: Science and Strategies for Restoring the Earth	Berger (1990)
River channel restoration: Theory and practice	Brookes (1995)
Rehabilitating Damaged Ecosystems	Cairns (1995b)
Riparian Land Management Technical Guidelines Vol. 1 and Vol. 2.	LWRRDC (1999a, b)
A Rehabilitation Manual for Australian Streams Vol. 1 and Vol. 2	Rutherfurd *et al.* (2000)
Guidelines for Stabilising Streambanks with Riparian Vegetation	Abernethy and Rutherfurd (1999)
Stream Corridor Restoration: Principles, Processes and Practices	FISCRWG (1998)
River Restoration	Petts and Calow (eds.) (1996)
River restoration- Danish experience and examples	Hansen (ed.) (1996)
Wise use of floodplains: Life environment project	Zöckler (2000)
Field manual of urban stream restoration	Newbury *et al.* (1998)
Bioengineering for Streambank erosion control	Hollis and Leech (1997)
Restoring streams in cities: A guide for planners, policy makers, and citizens	Riley (1998)
Urban stream rehabilitation through a decision-making framework to identify degrading processes and prioritise management actions	Walsh & Breen (1999)
River restoration: A comprehensive framework	Lucas *et al.* (1999)
Stream restoration lessons learned in North Carolina, USA	Jennings & Harman (1999)
River restoration manual of techniques: Restoring the River Cole and River Skerne	Vivash and Murphy (1999)

1.6 Problem statement

The documents listed in Table 1 are key stepping stones on the path to successful rehabilitation, however, they may be inadequate for the following reasons:

- they lack the detailed guidance that is necessary for people on the ground to understand and use. Documents that guide the process of rehabilitation, while at the same time offer possible solutions to particular problems experienced in the field are needed

- no manual exists which is specific to the South African situation
- the information presented in some of these manuals is often complex. A fair amount of reading and understanding is therefore needed to obtain the information required
- none of the documents deal with how to make a decision, instead information is given and the user is left to extrapolate from what he is presented with

The aim of SR-DSS is to circumvent these inadequacies by considering the information these documents have to offer and fill the gaps that are left by them. The aim is not to provide prescriptive type guidance, instead guiding principles (e.g. sustainability) are integrated into the design, in an attempt to gain essential input from the user who decides the objective and is familiar with the site.

Interest in streambank rehabilitation is expanding at a rapid pace to many parts of the world, especially in the light that environmental concerns, and more specifically, concern over water resources. More money is being spent on the stream rehabilitation effort, in general, as concerns over degraded rivers are taken more seriously. For example, a stretch of the River Cole in England, where the creation of a 2 kilometer long meandering river course, cost £140 000 (R2.1 million). On another project, 500 meters of the River Skerne (UK), where the creation of a new meander in the old, straight course, and the enhancement of the existing course cost £300 000 (R4.5 million). In Japan US$ 200 million (R1.6 billion) was recently spent to restore the waterways of Tokyo for recreational purposes (Gippel & Fukutome, 1998) and 1500 sites have been treated in a similar manner. In the United States, the rehabilitation of Biscayne Bay, a major Florida estuary, is estimated to have cost in the region of US$ 24 million (Thorhaug *et al.,* 1990), while in South Africa, the working for water program, which aims to clear riparian areas of exotic, water wasting species, is running into the millions of Rand (Versfeld *et al.,* 1998). Streambank rehabilitation is considered as fundamental for restoring a catchment. A stable bank, together with a healthy riparian structure of adequate zone width goes a long way to stabilise the entire catchment.

Various techniques are available to mitigate against bank instabilities. The question is which technique should be used, and when? Furthermore, rehabilitation efforts are commonly hampered by financial and other resource constraints. The key to a successful streambank rehabilitation venture is therefore to set priorities between catchment, reaches, and sites to minimise costs. It will be argued in the document, that resources would be better spent on reaches which are not yet fully degraded as opposed to fully degraded ones. To spend money on fully degraded reaches, while ignoring other reaches, while their values are being lost, will be more expensive in the long term than *vice versa*. Furthermore, the physical technique implementation is just a facet of streambank rehabilitation. Other issues need to be considered, such as evaluation, monitoring and post technique management. These issues will be considered in more detail in Chapter 2.

1.7 Aims and objectives

The aim of the document is to provide an approach that will guide users, through a streambank rehabilitation exercise. The aim is that the user is made aware of all aspects of riverbank rehabilitation and is encouraged to undertake the work holistically. The objectives of this research are to:

- review riparian and streambank rehabilitation techniques and processes. Particular attention will be given to the recent technical guidelines produced in the UK, USA and Australia
- identify principles for sound riverbank rehabilitation
- identify criteria for streambank rehabilitation technique selection
- consolidate information to a decision support system
- design a system for setting priorities between catchments or sites
- undertake preliminary testing of the rehabilitation approach and evaluate its utility
- re-examine SR-DSS and provide recommendations for future use

1.8 Methodology

A priority setting model and a decision support system for riparian bank rehabilitation techniques has been compiled from a literature review of numerous existing manuals designed for (and in) other parts of the world. Contributing documents included those referred to in Table 1. A review of riparian zone function and role as well as problems commonly associated with streambank rehabilitation has been included in this document. Streambank rehabilitation techniques have been gathered and organised into a flow chart which aims to assist users to identify appropriate rehabilitation techniques according to the required objective and the erosive forces that occur on a bank. This classification formed part of the input into a decision support system. As vegetation plays a pivotal role in bank stability, a sizable section of its role in streambank stability has also been included. The completed versions of the decision support system and priority setting model have been tested on the Foxhill Spruit in Pietermaritzburg, while testing during the course of its development took place on tributaries of the Tugela River at and near Tugela Mouth.

1.9 Structure of the Document

The document is consists of six chapters plus appendices. Chapter 1 deals with the motivation for the study, its underlying aims and objectives. It also describes the value of riparian areas, their functions and roles, and the state in which they are in. Chapter 2 includes a comprehensive literature review, which describes current understanding and theory of streambank rehabilitation, the methodology, and practices. Chapter 3 introduces the priority setting model and decision support system and attempts to include it into a broad framework for rehabilitation exercises.

Chapter 4 presents the results of the testing that took place on the Foxhill Spruit. These results include the recommendations given by the decision support system and the priority order set by the priority setting model. Chapter 5 appraises the performance of the rehabilitation approach that was conducted on the Foxhill Spruit. The recommendations given by SR-DSS are also scrutinised in the form of a table which questions if the techniques chosen by the decision support system are the most appropriate. Chapter 6 concludes the document by making recommendations as to the use of the decision support system and what is needed in the future. A glossary of terms used in the document is also included. Furthermore, an example on how to use SR-DSS is presented in Appendix 1 and the techniques used are presented in Appendix 2.

CHAPTER 2

Bank stability concepts and processes

2.1 Bank stability

2.1.1 Background

Bank stability has been widely studied in countries such as Australia, the UK and the USA. Early research on river bank erosion and lateral channel change was pioneered by researchers such as Wolman (1959), Schumm and Lichty (1963), and Twidale (1964). These authors focussed primarily on emphasising the rapidity of bank erosion, and the complexity of its process. Later contributions demonstrated the wide range of interplay of processes responsible (Knighton, 1973; Hooke, 1979; Thorne & Lewin, 1979; Kesel & Baumann, 1981; Thorne, 1982; Hickin, 1982; Lawler, 1987), as well as environmental controls (Dickinson & Scott, 1979; Hooke, 1980; Nanson & Hickin, 1986; LWRRDC, 1999a, b). Works contributing to this body of knowledge include the demonstration of the links between lateral migration and, for example, meander evolution (Hickin, 1974; Lewin, 1972, 1976; Mosley, 1975a), floodplain construction and destruction (Leopold, 1973; Lewin & Manton, 1975; Werrity & Ferguson, 1980; Nanson & Young, 1981) and the processes involving catchment sediment transport (Bello *et al.,* 1978; Bray, 1987; Duijsings, 1987). Biological diversity on floodplains, has also been known to be highly dependent on the lateral migration of river courses (Nanson & Beach, 1977; Salo *et al.,* 1986). Modelling and simulation work has had an exponential increase in importance in riparian management with the coming of the computer age (Begin, 1981; van der Valk, 1981; Pearlstine *et al.,* 1985; Malanson, 1993; Haschenburger, 1996, 1999), possibly sparked by enormous financial losses caused by streambank erosion amounting to sums exceeding US$ 270 million in the USA alone (United States Army Corps of Engineers, 1978). With such high losses, and economic development encroaching on many of the world's highly sensitive environments, river management problems have recently provided extra impetus to the field (Williams *et al.*, 1979; Scott, 1982; Bathurst *et al.,* 1986; Odgaard & Mosconi, 1987; Leeks *et al.,* 1988; Lawler, 1993).

2.1.2 Mechanisms by which banks destabilise

The erosion of streambanks may be grouped into three broad categories: sub-aerial erosion of the bank material; direct scour of bank sediment; and mass movement of material due to gravity (Hooke, 1979; Bowie, 1982; Thorne, 1982; LWRRDC, 1998, 1999b). All three processes act together along the length of rivers. It is their relative importance however, that varies at any one point down the catchment. It must be further noted that these processes can act simultaneously at a single point. The key to successful erosion management therefore, is to recognise the dominant erosion processes and to treat them appropriately. In order to get a better understanding of these three processes, they will each be examined more closely.

(i) Sub-aerial erosion

A variety of processes, which are largely external to river processes, may affect stream banks that are exposed to the air. Some of these processes affect banks directly, while others render them more vulnerable to erosion by weakening certain properties within the bank. Sub-aerial processes include (LWRRDC, 1999a, b):

- windthrown trees
- damming by large woody debris
- frost heave
- desiccation leading to cracking and ped dislocation
- rain splash and micro-rill dislocation
- slaking
- stock trampling

Incidences in which trees are windthrown, sediment is delivered into the water when their rootballs detach from the bank. These situations are often complicated further when flow is redirected against the exposed bank as a direct result of snagging. Windthrow problems are maximised when trees occur in a single line along the bank top (Thorne, 1990) and where wind velocities exceed 40 km/hr (Coppin & Richards, 1990). In this sense, a wide bank of trees is preferable (Thorne, 1990). Frost heave may significantly contribute to increased levels of bank erosion in cold regions (Lawler, 1986). Needle ice forms in conditions, where there is a sufficient moisture supply, appropriate soil pore geometry, limited vegetation, and sub-zero temperatures, to lift up soil particles. Particles are therefore more easily removed. When bank materials dry out, they crack and weaken it, making it more prone to erosion. Knighton (1973), indicates that this may have a greater effect on bank erodibility than bank material composition itself. Similarly, rain splash and rill development also have a role to play in bank erosion. When a rain drop hits the soil surface, kinetic energy, which is transferred, causes dislodging and the particles may be carried away in the ensuing flow. Slaking occurs as a result of rapid immersion of the streambanks. Air pockets form when water enters the dry soil aggregate. As more water enters the soil, so the air pockets become compressed, and pressure builds up. Should the soil aggregate's mechanical strength be sufficiently low, the compressed air will shatter it, causing loss of structure and further vulnerability to erosion. Banks are also made more vulnerable by stock trampling and grazing which reduces the vegetative cover. Areas are thus exposed to the elements. Also, stock trampling breaks down banks and transfers large quantities of bank material into the flow.

Although active on exposed banks on all parts of the catchment, sub-aerial erosion usually plays a small role in bank erosion when compared to the processes of scour and mass failure. Sub-aerial erosion is usually apparent when these other erosion processes are limited, and therefore tend to be more important in small upper catchments and in the dispersive soils of gullies. However, sub-aerial erosion can be the precursor of erosion by scour which is especially true of dessication. One way to determine this is to look at the erosion processes that are isolated from the main flow, such as cut off meander bends or old channels (LWRRDC, 1999b).

(ii) Scour

When the force applied to a bank by flowing water exceeds the resistance of the bank surface to withstand those forces, scour occurs. The potential for a bank to be eroded by scour is traditionally described by flow shear stress, which is a measure of the drag exerted on a unit area of the channel perimeter which, in turn, is a function of flow depth and slope (LWRRDC, 1999b). If the internal resistance of the bank is exceeded by the shear stress, particles may become dislodged and entrained in the flow (Thorne, 1982). Scour is usually most pronounced on the outside of meander bends.

Vegetation profoundly decreases the potential for a bank to scour because it affects both force exerted on the bank and the bank's ability to resist that force. Force is affected by creating back waters that slow flow against the bank face and weaken circulation bends (Thorne & Furbish, 1995). Since the boundary shear stress is proportional to the square of near bank velocity, a reduction in flow velocity produces a much greater reduction in erosion. Vegetation traits, which are important in reducing erosion include: its rigidity, type and density. The influence of vegetation on bank scour is discussed in more detail below (see section 2.2.3).

(iii) Mass failure

Mass failure occurs if whole blocks of materials slide or topple into the water when the strength of the bank aggregate is too low to resist gravitational forces (FISCRWG, 1998). This form of bank erosion typically occurs in floodplain reaches, where the banks usually consist of cohesive material resistant to scour and instead are more prone to be eroded by mass failure (LWRRDC, 1999b). Banks that are collapsing, or are about to collapse, for instance, where the removal of the toe slope support leads to instability, are referred to as being geotechnically unstable. The rate of bank erosion due to mass failure depends on the relationships among gravitational forces acting on the bank material, the hydrostatic pressure on the bank material, the bank's resistance to mass failure, the geometry of the bank section, the physical properties of the bank material, and the type and density of vegetation.

Natural streambanks are commonly composed of distinct layers exhibiting the depositional history of the bank materials. Each individual sediment layer can have physical characteristics quite different from those of other layers. For instance, composite banks, consist of a coarse non-cohesive layer that is covered by a fine grained cohesive upper layer. The bank profile will therefore respond according to the physical attributes of each of the layers. Since the stability of streambanks with respect to failures due to gravity, depends on the geometry of the bank profile and the physical properties of the bank materials, dominant failure mechanisms tend to be closely connected with characteristic stratigraphy of succession of layers. A steep bank, consisting of uniform layers of cohesive or cemented soils generally develops tension cracks (Figure 1a, b) at the top of the bank, corresponding to the bank alignment (Figure 2). Slab failures result when the weight of the soil exceeds the strength of the grain to grain contacts within the soil material, as a direct consequence of scour or water flowing out of the bank taking with it small clay particles. As the clay content, or the cementing agent decreases, the slope of the bank elevates; vertical failure planes become more flat and planar failure surfaces develop. Rotational failures (Figure 3) occur as described above, except the bank soils are predominantly cohesive. Block-type failures (Figure 4) occur when a weak soil layer is eroded away and the layers above the weak layer lose structural support. Large scale slumping of the bank usually happens after the banks have been saturated due to precipitation or high stream events. The water adds weight to the soil and reduces grain-to grain contacts and cohesion forces while intensifying the pore pressure. Pore pressure (or hydrostatic pressure) occurs when soil water in the pore cavities is under pressure from overlying soil and water. Pore pressure is therefore internal to the soil mass. When a stream is full, the flowing water provides some support to the streambanks. When the stream level drops, the support is removed and the internal pore pressure pushes out from within and increases the potential for bank failure (FISCRWG, 1998). Depending on the bank materials, what is referred to as wet earthflow may result (Thorne, 1998). The physical properties of the bank profile should therefore be defined to aid in the characterisation of potential stability problems and identification of dominant mechanisms of bank instability.

Ground water sapping or piping is another means by which banks fail (Figure 5). Sapping, or piping, is the erosion of soil particles beneath the surface by flowing ground water. Dirty or sediment laden seepage from a streambank is evidence of ground water sapping or piping taking place. Soil layers above the areas of ground water piping will eventually collapse (Figures 5.1 to 5.3) after enough soil material has been removed from the support layer (Hagerty, 1991; FISCRWG, 1998).

The level of intensity of geotechnical investigations varies in their planning and design. During planning, enough information must be collected to ascertain the feasibility of the alternatives being considered. For example, qualitative descriptions of bank stratigraphy obtained during planning may be all that is necessary for identifying dominant modes of failure in a study reach. Thorne (1992) describes stream reconnaissance procedures particularly for recording streambank data.

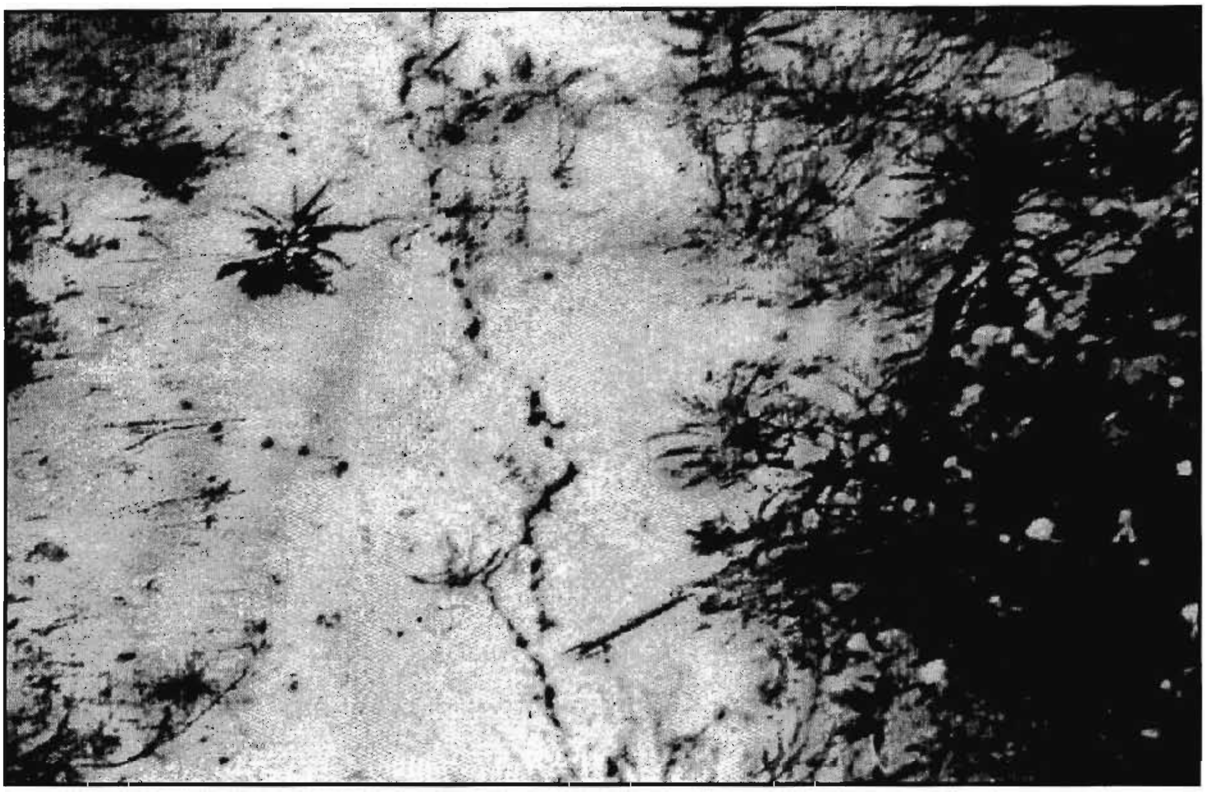
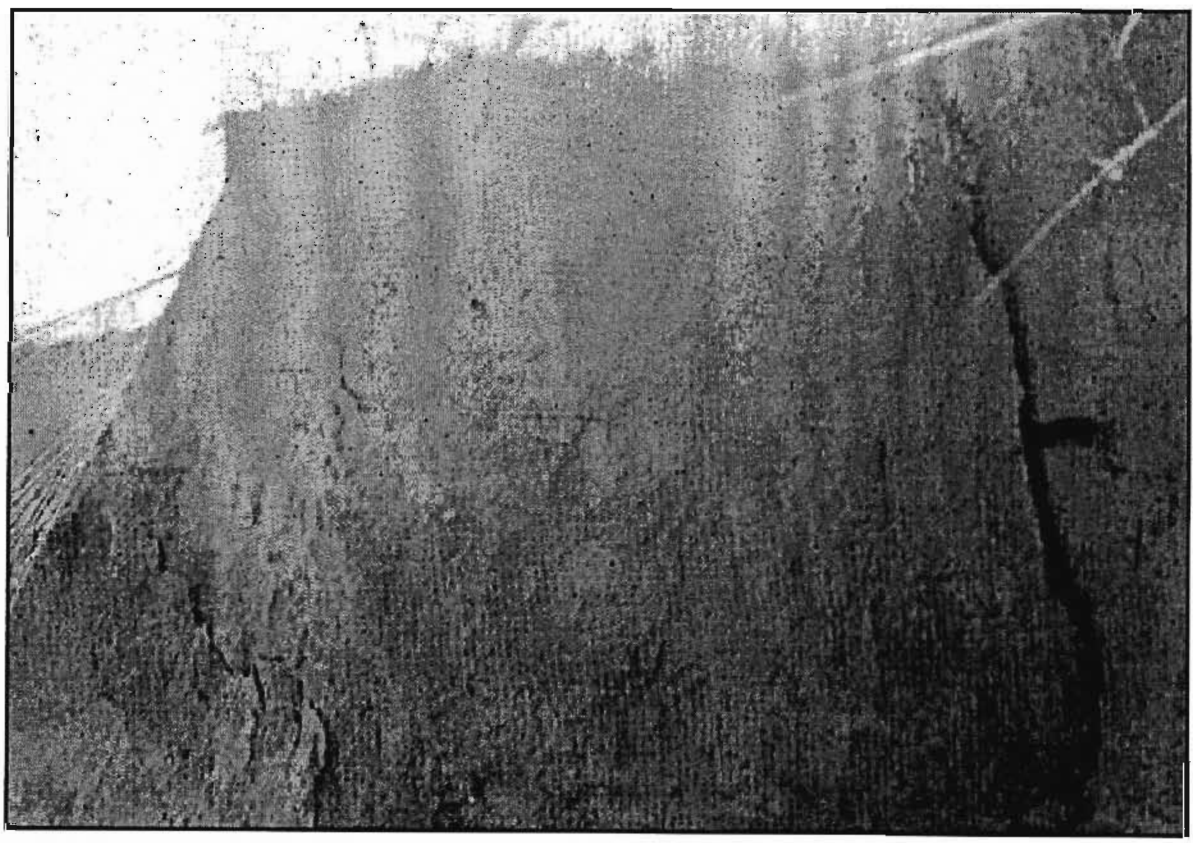
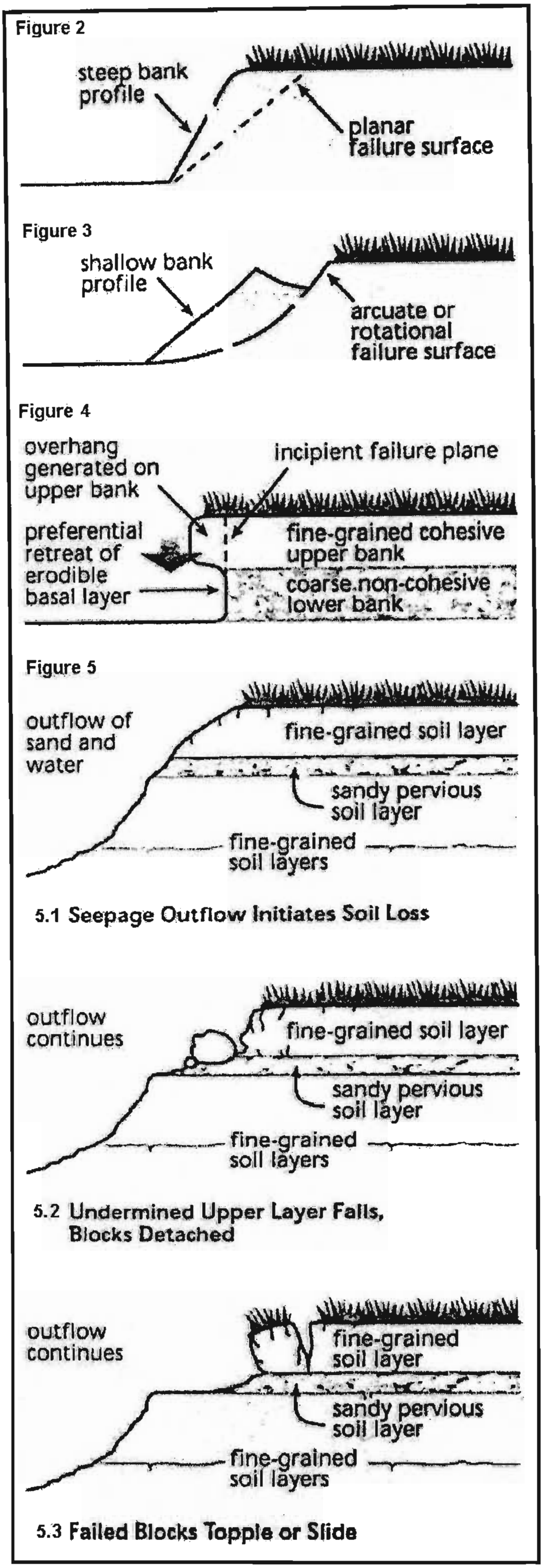


Figure 1: Tension cracks on a steep, actively eroding streambank. Above: Crack forming in the floodplain surface behind the bankline; Below: a wide crack behind the failure block (Thorne, 1998).





Figures 2 - 5,3: The relationship between dominant bank failure processes and related stratigraphy. **Figure 2**: Uniform bank profile undergoing a planar type failure. **Figure 3**: Uniform bank profile undergoing rotational type failure. **Figure 4**: Cohesive upper layer and non-cohesive lower layer leading to cantilever type failure process. **Figure 5, 5,1 - 5,3**: A complex bank stratigraphy may lead to piping or sapping type failures. (FISCRWG, 1998).

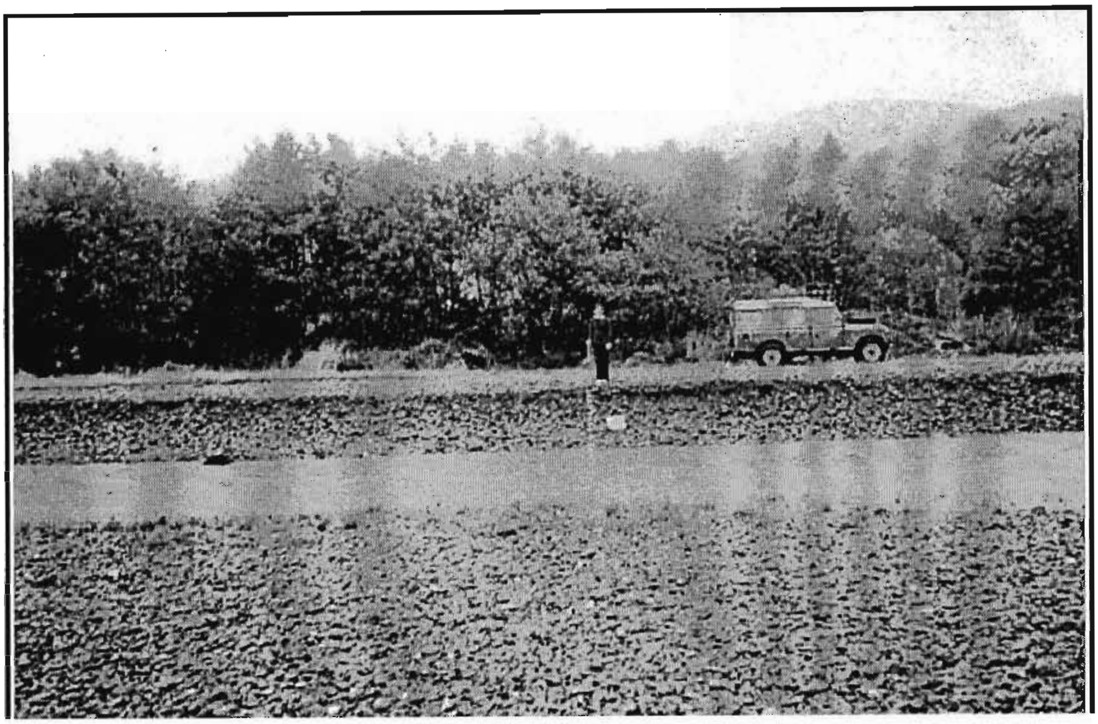
2.1.3 Measuring bank erosion

Although outer banks of meanders erode, erosion rates range greatly from stream to stream and bend to bend. Inspection of the project stream and comparable reaches, merged with professional judgement may be adopted to determine the need for bank protection, or erosion may be approximated by simple rules of thumb. These may be based largely on studies that relate bend migration rates to bend geometry (Apmann,1972, Odgaard, 1987). More precise estimation of the rate of erosion of a given streambank is beyond current technology. The most precise and accurate is the erosion pins technique, and various other tools, which have been developed more recently. None of these have been used in exceptionally diverse settings, and users should view them with caution (FISCRWG, 1998).

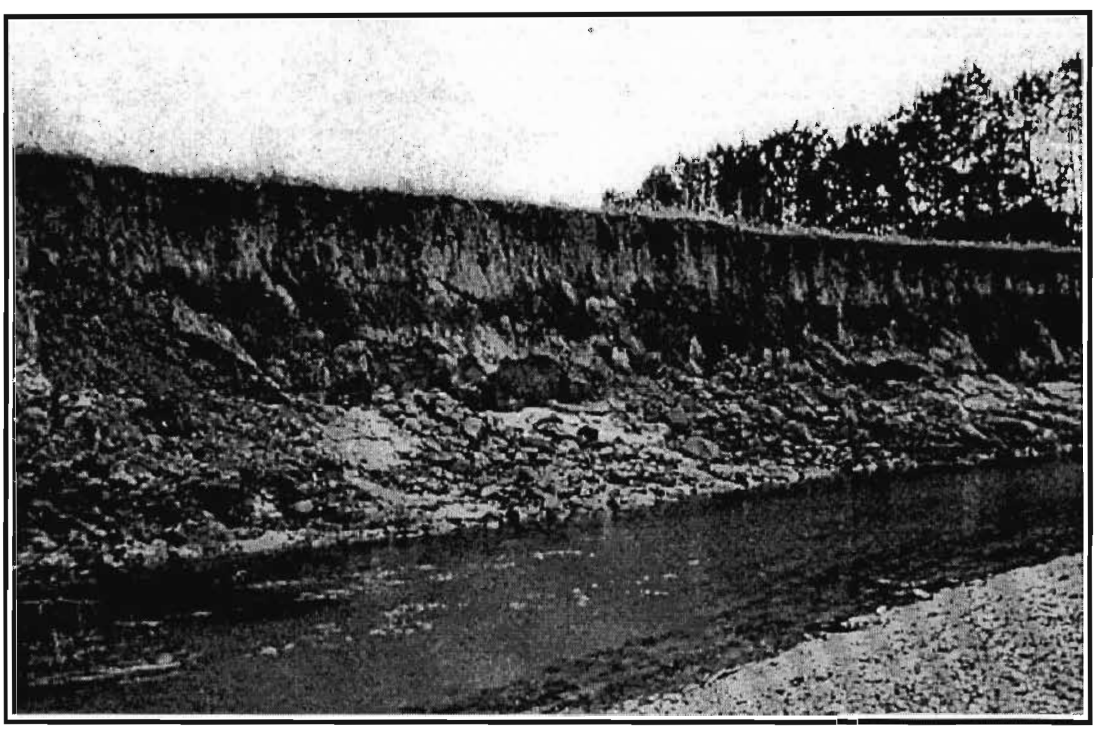
Nevertheless, a wide range of bank erosion and lateral channel change measurement techniques are available (Lawler, 1993). Methods have varied because of the wide range of fluvial environments encountered, the range of spatial and temporal scales of enquiry, the differing aims and objectives of research explorations, and the trans-disciplinary backgrounds of the body of researchers undertaking the task. Although progress in bank erosion measurement has been greatly enhanced through the contribution of many disciplines, there is no standardisation of techniques, and results are scattered throughout the literature.

There are seven main techniques for measuring the rate of river bank erosion and lateral channel change through time and space (Lawler, 1993). These are, sedimentological evidence from valley fills, botanical evidence from floodplain surfaces and deposits, serial historical sources, planimetric surveys, repeated cross-profiling, erosion pins, and repeated terrestrial photogrammetric surveys. Much of the early work concentrated on detecting bank erosion from historical sources only (Fergusson, 1863; Shillingford, 1895; Duncanson, 1909; Smith, 1910; Bryan, 1927, 1928; Goldwaite, 1937; Boggs, 1940). However, as research began to get more sophisticated, field-based methods achieved more popularity, stimulated by the classic research by Wolman and Leopold (1957) and Wolman (1959). These techniques will be briefly looked at here, however Lawler (1993) provides a detailed description of the seven bank erosion techniques mentioned above. Lawler (1993), revealed that no one technique emerged singularly popular nor has any one method become completely obsolete. All are still being used, although, the use of field-intensive methods, as opposed to methods based purely on sedimentological or botanical evidence, show signs of recent popularity.

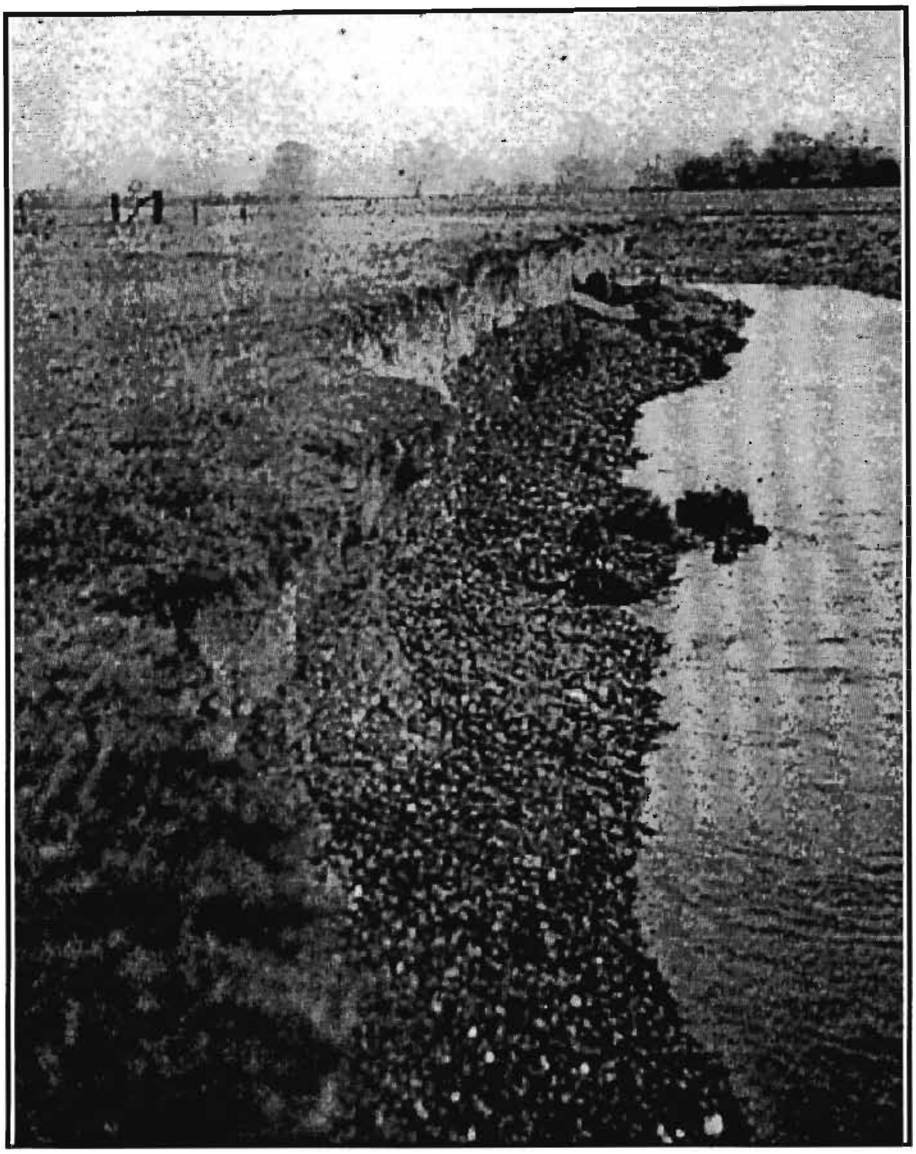
Bank types referred to in the text (Thorne, 1998).



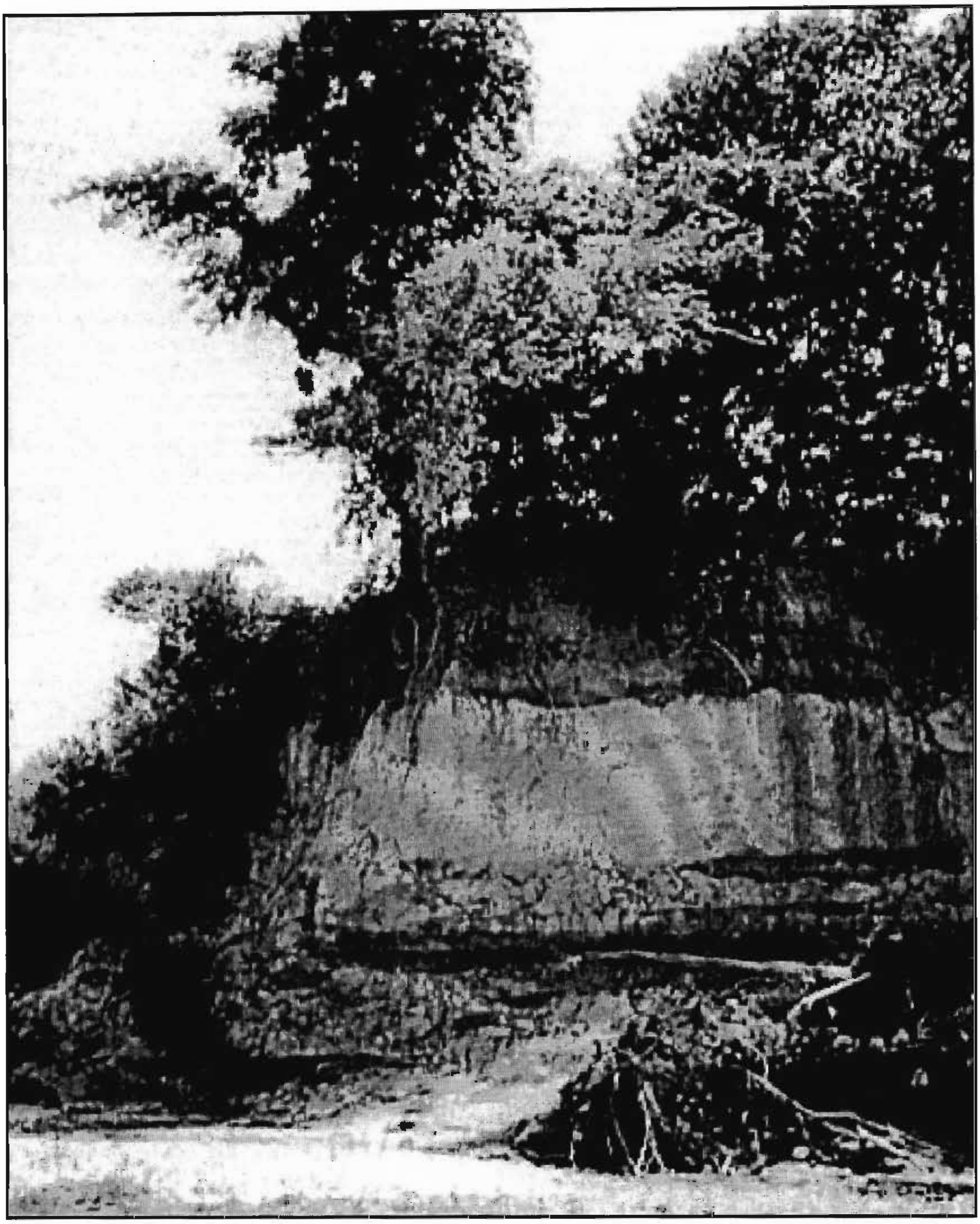
a) non-cohesive: bank materials are loosely arranged and offer no resistance to erosive forces. They are formed in sands, gravels, cobbles and boulders that lack intrinsic cohesion.



b) cohesive: bank materials cling to each other and offer some resistance to erosive forces although this is not enough for complete protection. Bank heights may be greater than in the case of non-cohesive materials.

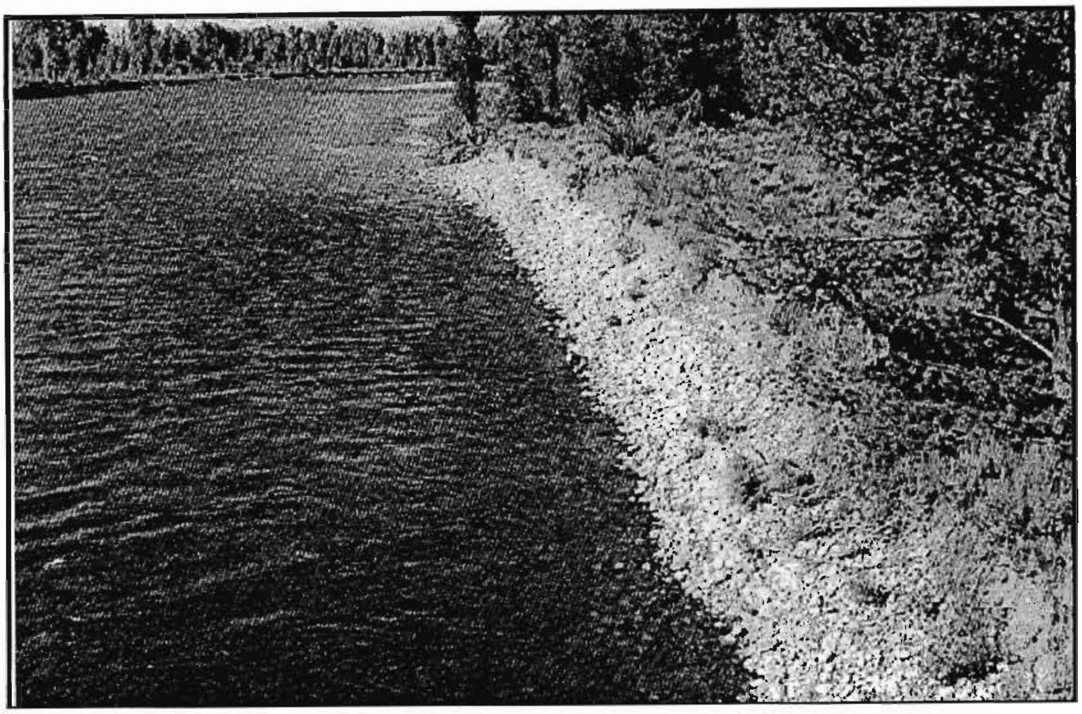


c) composite: consist of a single cohesive layer underlain by a single non-cohesive layer. Such banks are common in streams with non-cohesive bed materials which are flowing through alluvial floodplain deposits consisting of bed materials laid down during past aggradational phases.

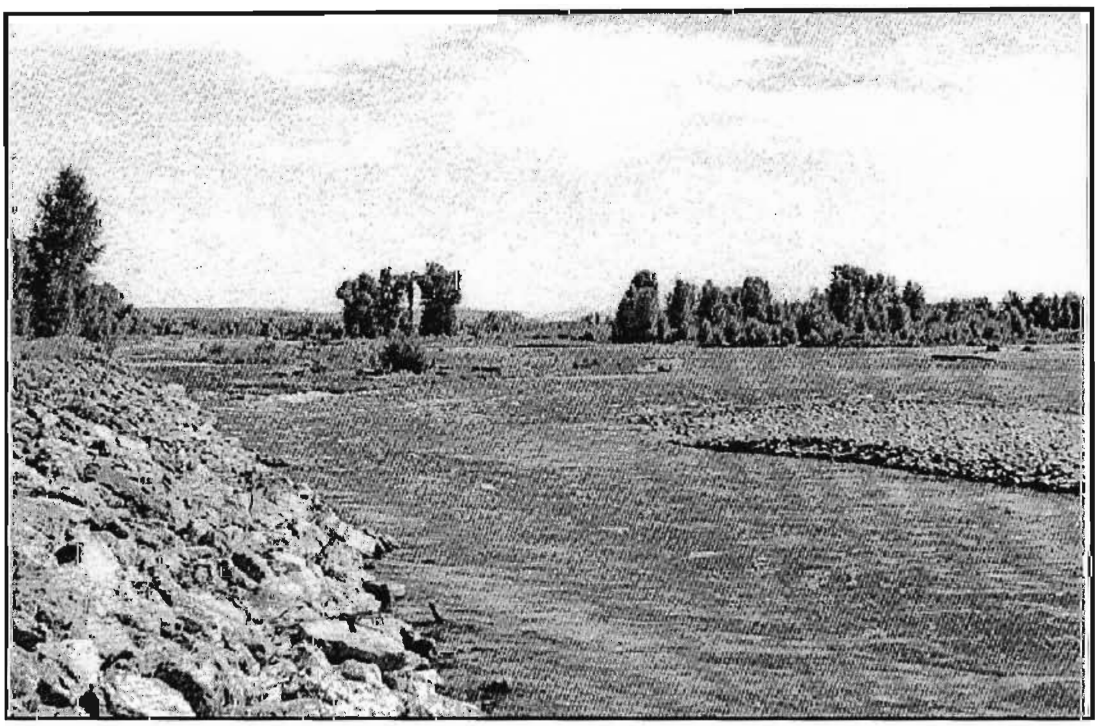


d) layered: consist of layers of non-cohesive and cohesive materials laid down during past aggradational phases. They are often of uneven thickness which can be significant to bank erosion and hydrology.

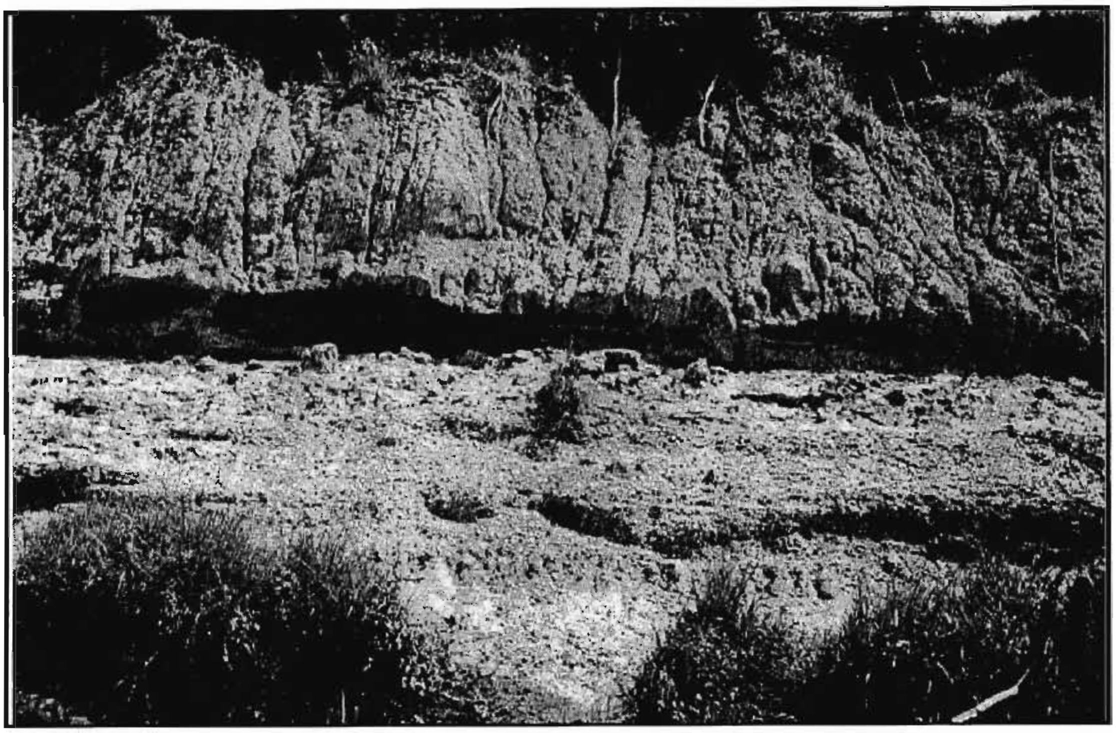
Bank erosion processes observed in the field (Thorne, 1998).



a) parallel flow: this form of erosion involves the removal of intact grains from the bank face by flow along the bank.



b) impinging flow: a form of erosion which detaches grains or aggregates of grains by flow attacking the bank at an oblique angle to the long-stream direction.

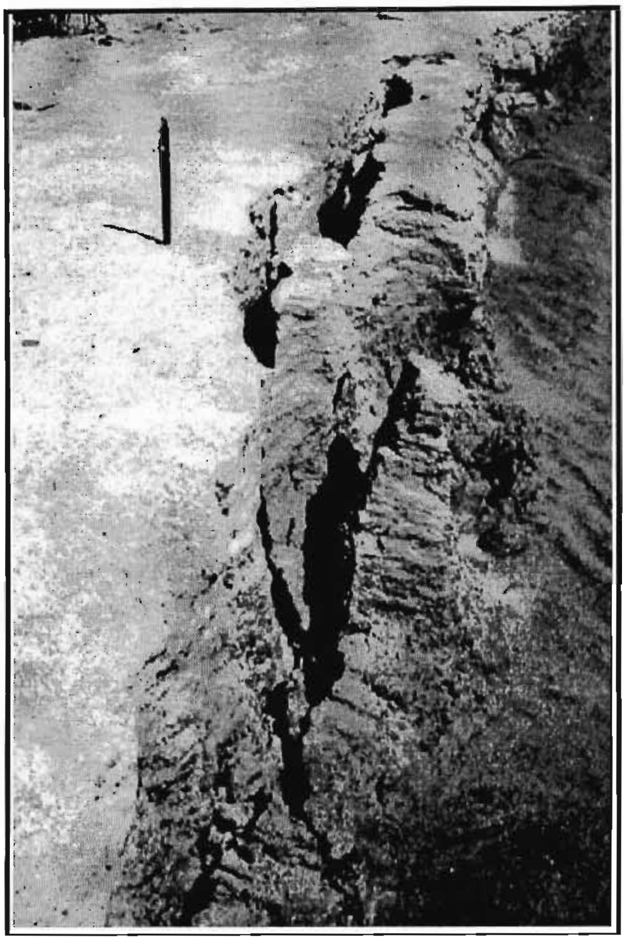


c) piping: is caused by groundwater seeping out of the bank face. Grains are detached and entrained by the seepage flow and may be transported away from the bank face by surface runoff.

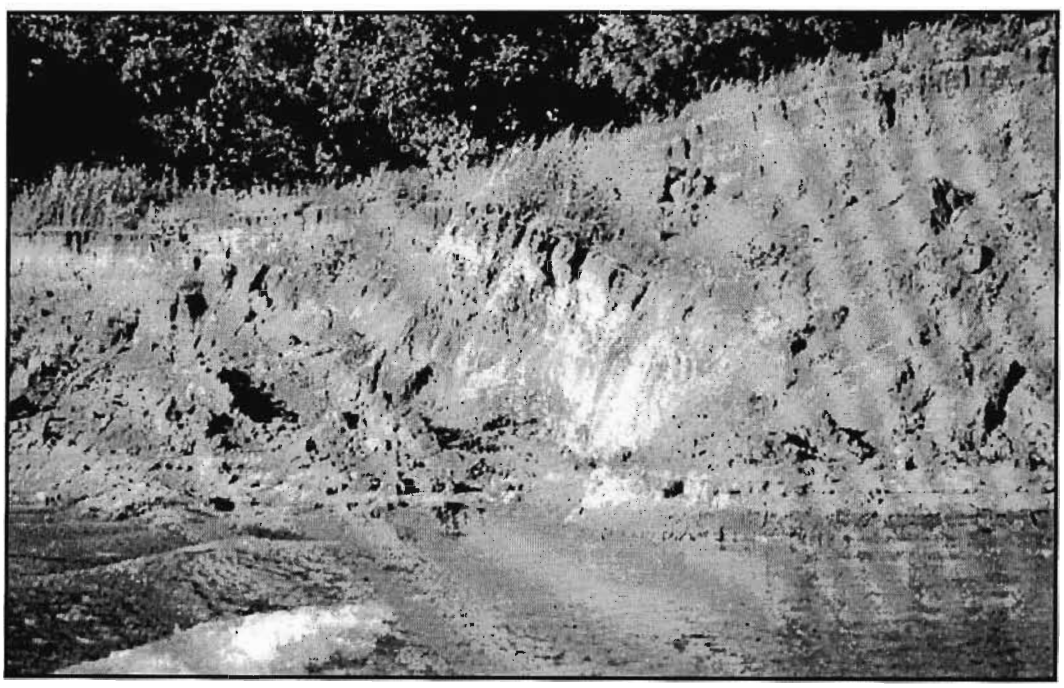
d) sheet erosion plus major rilling and gullying: is the removal of soil by non-channelised (sheet erosion) and channelised (rilling and gullying) surface runoff. It results from surface water draining over the bank edge, especially where the riparian and bank vegetation has been destroyed.

f) wind waves: cause near-bank velocities and shear stresses to increase and generate rapid water level fluctuations at the bank.

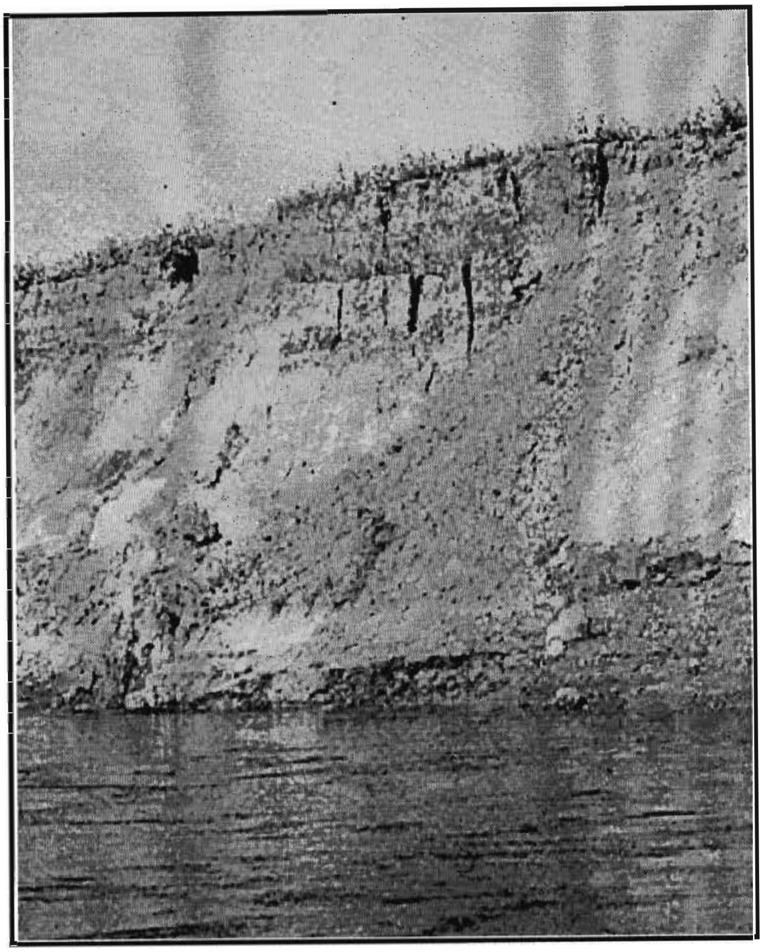
Modes of geotechnical streambank failures observed in the field (Thorne, 1998).



a) major soil fall: occurs only on steep banks, where grains, grain assemblages or blocks fall into a channel. Such failures are found on steep, eroding banks of low operational cohesion.

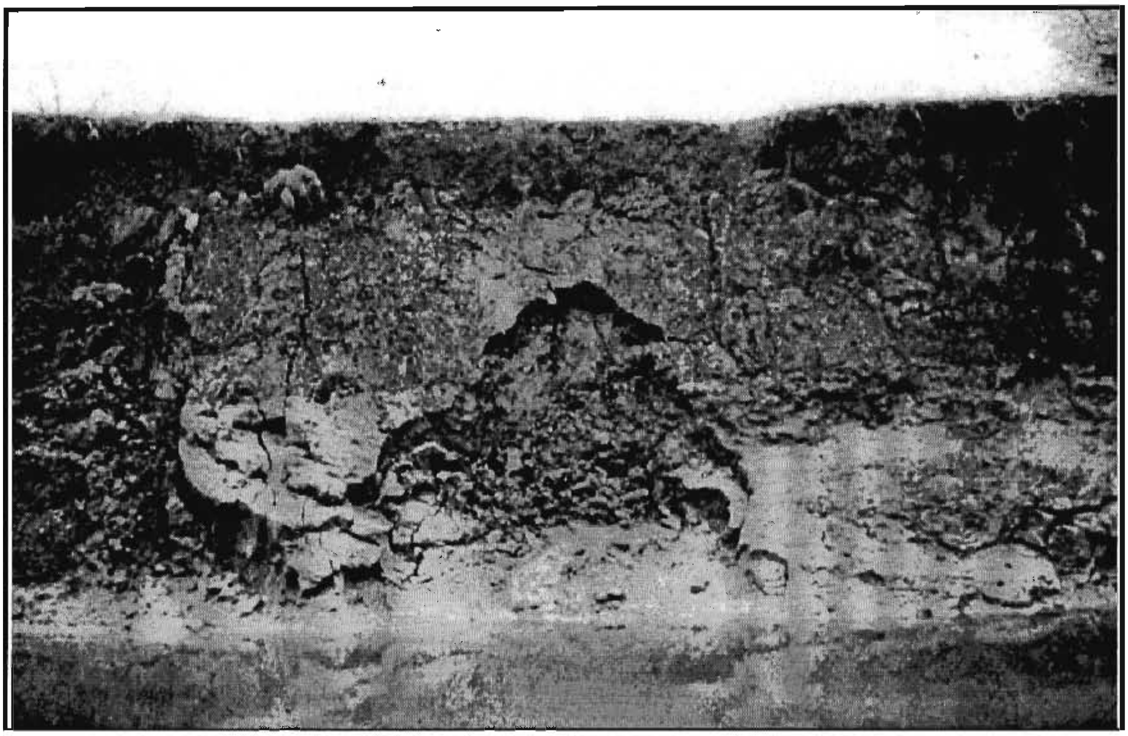


b) rotational failure: most widely recognised form of bank failure. A deep-seated failure along a curved surface results in back-tilting of the failed mass towards the bank.

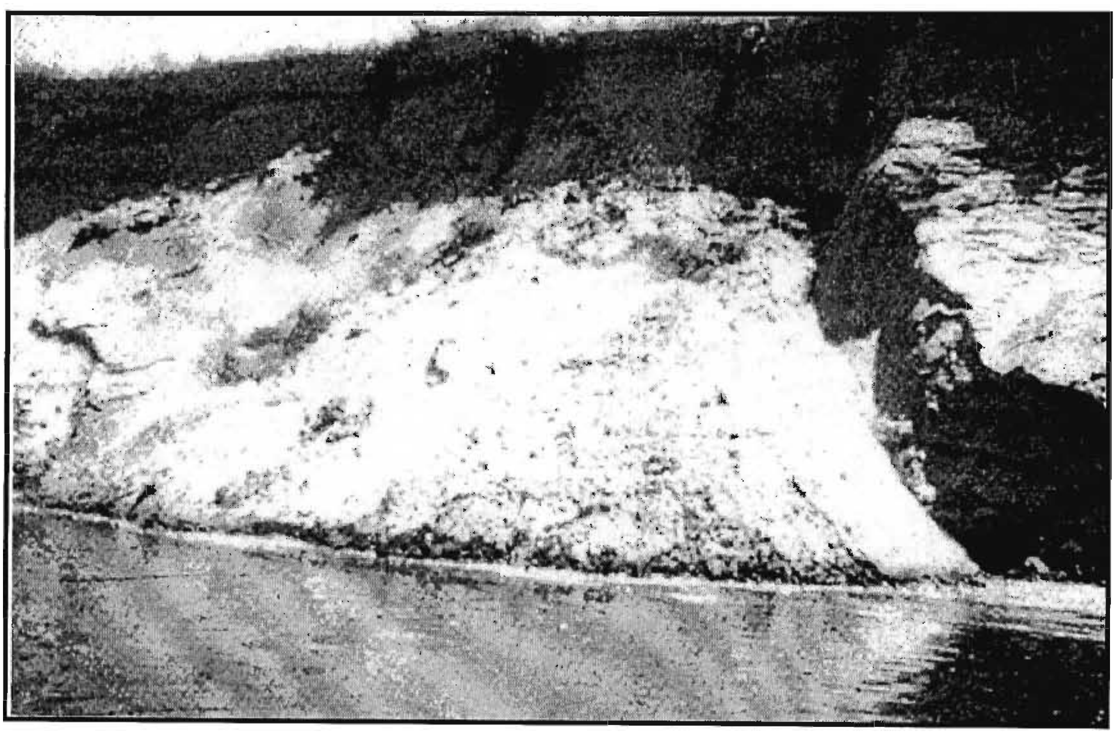


c) slab failure: is the sliding and forward topling of a deep-seated mass into the channel.

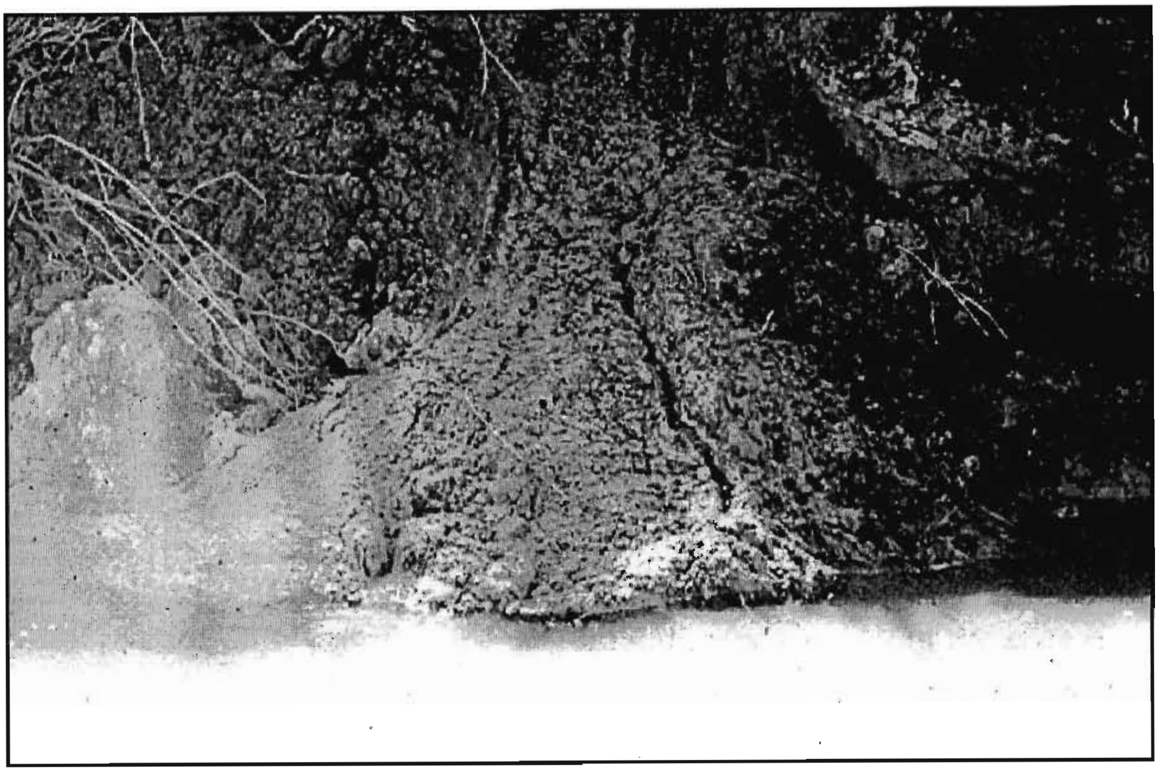
d) cantilever failure: the collapse of an overhanging block into the channel.



e) pop-out failure: results from the saturation and strong seepage in the lower half of a steep cohesive bank. A slab of material in the lower half of the steep bank face falls out, leaving an alcove-shaped cavity.



f) dry granual flow (soil fall): such failures occur when a non-cohesive bank, at close to the angle of repose, is undercut, increasing the bank angle above the natural angle of repose, causing soil fall to occur.



g) wet earth flow: is the loss of strength of a section of bank due to saturation, when water logging of a bank increases its weight and decreases its strength to the point that the soil flows as a highly viscous liquid.

h) a common form of bank failure caused by cattle grazing and trampling: grazing animals cause degradation in two ways 1) by physically breaking the bank structure down and loosening the soil with their hooves, and 2) by reducing the vegetation so that its bank supporting role is reduced.

(i) Sedimentological evidence

This technique centres on establishing an alluvial chronology based on preserved sequences of fluvial deposits which can be dated. Although used extensively to reconstruct valley floor histories, few specifically concern lateral river activity and migration rates (Lawler, 1993).

(ii) Botanical evidence

Of at least four different botanical methods, dendrochronological dating is the most commonly used. It involves the identification of the relative age of floodplain vegetation to produce the rate and pattern of lateral channel change. Dendrochronology has become a widely used technique for dating, which includes landscape events (floods, fires, volcanic eruptions etc.). It has a far greater dating resolution than just about any other technique, and has formed the basis of calibration for the radiocarbon timescale. (Eardley, 1938; Everitt, 1968; Hickin & Nanson, 1975; Salo *et al.,* 1986).

(iii) Historical testimonies

There have been a great number of researchers who have turned to historical sources to trace channel movements over the last 150 years (Fergusson, 1863; Bryan, 1927, 1928; Johnson & Painter, 1967; Swenson, 1970; Lewin, 1976; Hooke, 1980; Sherstone, 1982; Leeks *et al.,* 1988). Sources which are typically available are maps, aerial photographs, surveyor's notes, and diaries (Lewin & Hughes, 1976). A common problem experienced by researchers using maps, particularly old ones, is that they contain a certain amount of error (Hooke & Perry, 1976). Hooke and Kain (1982) and Hooke and Redmond (1989) provide useful guidance on sources of error and methods of checking maps which may contain error.

(iv) Planimetric resurvey

This method may be employed in a number of ways, the most common being, plane-tabling, baseline resurvey (Chain-and-offset mapping), tacheometric methods and electronic distance measuring or EDM (Lawler, 1993). Successive surveys are compared to detect any changes. Planimetric resurvey became a popular method in the 1970's with researchers such as Pugh (1975) and Bannister and Raymond (1977).

(v) Repeated cross-profiling

This method involves the levelling of the profile at various intervals on sections of the river to record recession of the total river bank and changes which may be occurring in other sections, such as accretion of point bars and bed form development. As for planimetric resurvey and historical records, subsequent profiles are compared to reveal any changes that have occurred through time. Various forms of this method include, levelling (Lawler, 1977), datum (Park, 1975), theodolite (Brown, 1971), A-frame (Riley, 1969), profile gauge (Mosley, 1975b), transit stadia (Kilpatrick & Barnes, 1964), inclinometer (Kesel & Baumann, 1981), plumbing (Dury, 1966), depth sounding (Matthes, 1955), and continuous seismic reflection profiling and/or sidescan sonar (May, 1982).

(vi) Erosion pins

This method has remained largely unaltered since the studies of Ireland *et al.* (1939) and Wolman (1959). It involves a thin plastic or metal pin which is inserted into the bank profile so that only a small, known, portion remains visible. As erosion takes place, more of the pin is exposed. Measurements from the end of the pin, to the bank are taken at regular intervals to detect the removal of material.

(vii) Terrestrial photogrammetry

Terrestrial photogrammetric determination of river bank erosion rates appears to have a great deal of potential (Lawler, 1989). It involves the use of photographic stations which are set up along the river bank at specific locations which are calculated to provide appropriate overlap to give a three-dimensional view of the bank. The photogrammetric cameras are integrated with a theodolite lens, to take stereoscopic pairs of photographs which give the three-dimensional effect. Subsequent recordings are compared to detect any change in the bank profile.

2.1.4 Quantitative assessment of bank stability

When rehabilitation designs require more quantitative information on soil properties, additional detailed data needs to be collected (Figure 6). For instance, values of cohesion, friction angle, and unit weight of the bank material may need to be quantified and recorded. Because of spatial variability, careful sampling and testing programs are essential to minimise the amount of data required to correctly quantify the average physical properties of individual layers or to determine a bulk average statistic for an entire bank. Care must be taken to characterise soil properties not only at the time of measurement but also for the 'worst case' scenario at which failure is expected (Thorne *et al.*, 1981). Unit weight, cohesion, and friction angle differ as a function of moisture content. It usually is not feasible to directly measure bank materials under worst case conditions, due to the hazardous nature of unstable sites under such conditions. It is recommended that a qualified geotechnical or soil mechanics engineer estimate these operational strength parameters. It is at this point that the author wishes to point out that the reader is not expected to fully understand the mathematics behind the following calculations. This section was included to give a brief insight into geotechnical aspects of bank stability. Should the reader require more information, Thorne, 1990; Yang, 1996; Trimble, 1997;

FISCRWG, 1998; and Harmel *et al.*, 1999 may provide further information.

Quantitative analysis of bank instabilities is considered in terms of force and resistance. The shear strength of the bank material characterises the resistance of the boundary to erosion by gravity. Shear strength is composed of cohesive strength and frictional strength. For the case of a planar failure of unit length, the Coulomb equation is applicable (FISCRWG, 1998):

$$Sr = c + (N - \mu) \tan \Phi$$

where,

Sr = shear strength, ($kg.m^{-2}$)

c = cohesion, ($kg.m^{-2}$)

N = normal stress, ($kg.m^{-2}$)

μ = pore pressure, ($kg.m^{-2}$)

Φ = friction angle

and where:

$$N = W \cos \theta$$

where,

W = weight of the failure block, ($kg. m^{-2}$), and,

θ = angle of the failure plane, in degrees (Figure 6).

While, the gravitational force acting on the bank is:

$$Sa = W \sin \theta$$

Factors that reduce the erosion resistance (Sr), such as excess pore pressure from saturation and the evolution of vertical tension cracks, favour bank instabilities. Similarly, increases in bank height (due to undercutting) favour failure by increasing the gravitational force constituent. In contrast, vegetated banks are generally drier and provide more bank drainage than unvegetated banks, which enhances bank stability. Plant roots provide tensile strength to the soil resulting in reinforced earth that substantially resists mass failure, at least to the depth of the plant roots (Thorne, 1990; Yang, 1996; Trimble, 1997; FISCRWG, 1998; Harmel *et al.*, 1999).

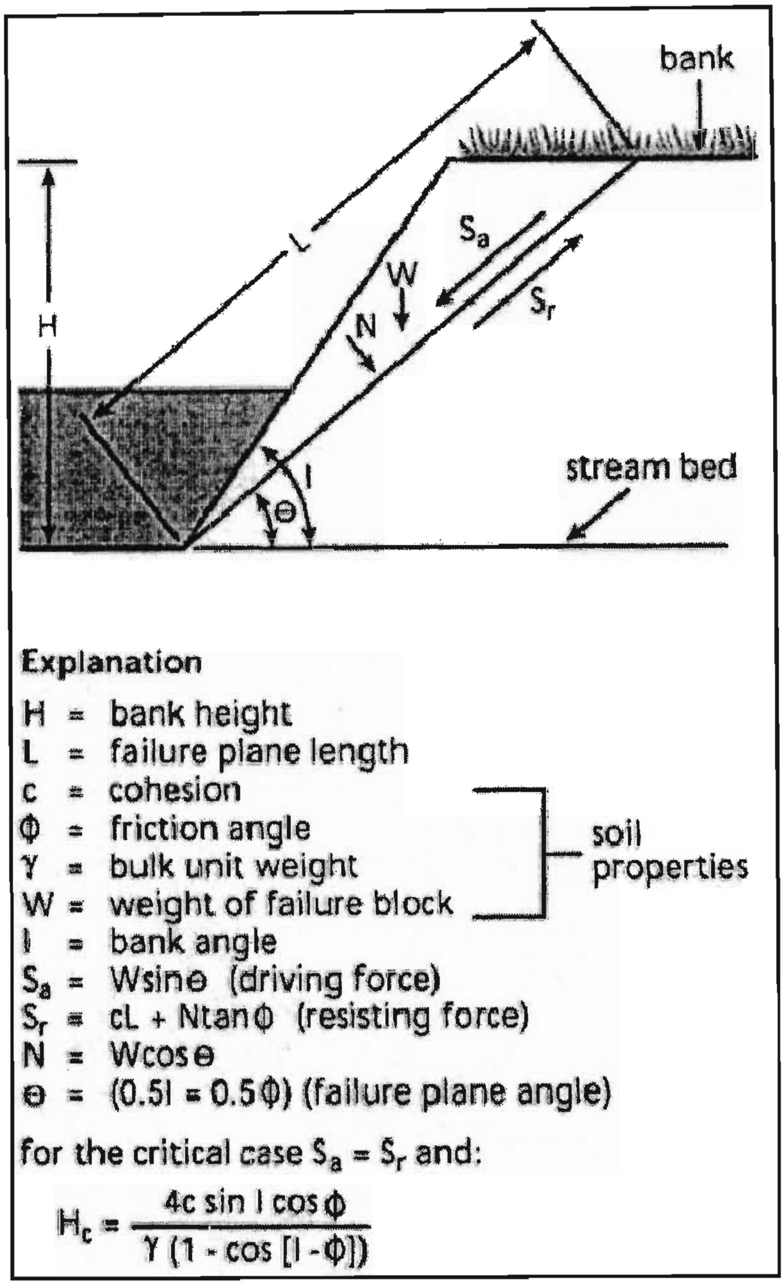


Figure 6: Forces acting on the bank (excluding pore pressure). Bank stability analyses are related to the strength of the bank materials and to bank height and angels, and also to soil moisture conditions (FISCRWG, 1998).

(i) Bank stability charts

In some cases, degradation on the streambank may be of such a nature as to require the input of a qualified engineer. These cases may occur where the bank is too high, the vulnerability of an important structure close to the bank may be too great, or the very nature of the bank materials would not lend themselves to the support of regular streambank rehabilitation techniques. Where a high degree of accuracy and analysis is required, a river engineer may refer to bank stability charts. These make it possible to establish a critical bank height in relation to the bank slope, moisture conditions, cohesive properties of the bank materials etc. To produce bank stability charts such as the one below (Figure 7), a stability number (*Ns*) representing a simplification of the bank (slope) stability equations, is used. The stability number is a function of the bank-material friction angle (Φ) and the bank angle (*i*) and is acquired from a stability chart. Numerous authors have developed bank stability charts, examples include, Chen (1975) (Figure 7) and Lohnes and Handy (1968).

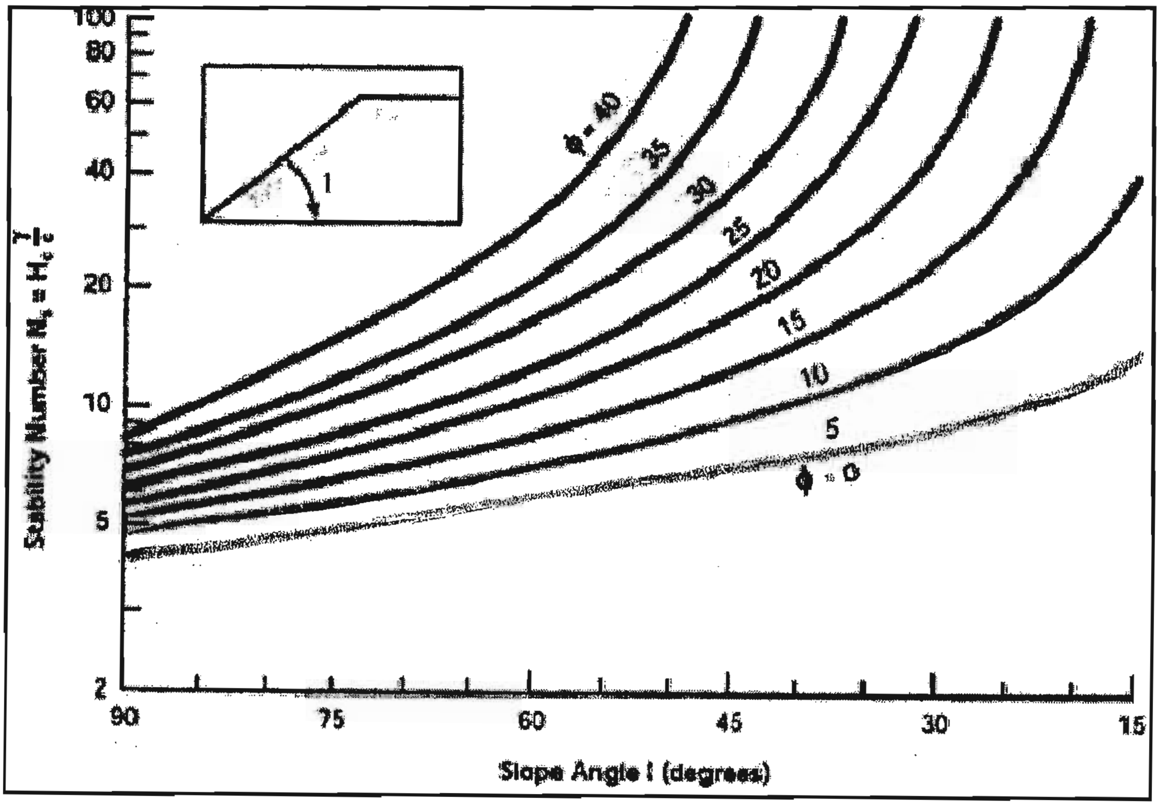


Figure 7: Chart providing the critical height for worst case condition. The stability number (*Ns*) is a function of bank angle (*i*) for a failure surface passing through the bank toe (Chen 1975).

The stability number (*Ns*) is calculated by:

$$Ns = \frac{4 \sin i . \cos \Phi}{1 - \cos(i - \Phi)}$$

where,

i = bank angle

Φ = friction angle

Once this has been calculated, H_c, or the critical bank height, where driving force (*Sa*) = resisting force (Sr) for a given shear strength and bank geometry, is computed (Carson & Kirby, 1972):

$$Hc = Ns(\frac{c}{\gamma})$$

where,

c = cohesion, (kg. m $^{-2}$), and,

γ = bulk unit weight of soil (kg. m $^{-3}$)

Equations are solved for a range of bank angles, using average or ambient soil moisture conditions to produce the upper line, or "Ambient field conditions, unsaturated." Critical bank height for worst-case scenarios (saturated banks and rapid decline in river stage) are obtained by solving the equations, assuming that Φ and the frictional component of shear strength goes to 0.0 (Lutton, 1974) and by utilising a saturated bulk-unit weight. These computations are represented by the lower line, or "saturated conditions."

The frequency of bank failure for the three stability classes (unstable, vulnerable, and stable, see Figure 8) is subjective and is based primarily upon empirical field data (FISCRWG, 1998).

- An unstable channel bank can be expected to fail at least annually and possibly after each significant stormflow in which the channel banks are saturated, assuming that there is at least one significant stormflow in a given year.
- Vulnerable conditions translate to a bank failure every 2 to 5 years, again assuming that there is a significant flow event to saturate the banks and to erode toe material.
- Stable banks, by definition, do not fail by mass wasting processes. However, channel banks on the outside of meander bends may experience erosion of the bank toe, leading to over steepening of the bank profile and eventually to bank caving incidents.

Generalisations about critical bank heights (H_c) and angles can also be made with experience of the variability in cohesive strengths. For example, categories of cohesive strength of channel banks may be distinguished. Critical bank heights above the mean low-water level and saturated conditions can be utilised to produce the figure because bank failures typically occur either during or after the deflation of peak flows. The result is a nomograph giving critical bank heights for a range of bank angles and cohesive strengths that can be used to predict stable bank configurations for worst-case conditions, such as saturation during rapid decrease in river stage. For more information on bank stability charts and critical bank heights, see FISCRWG (1998).

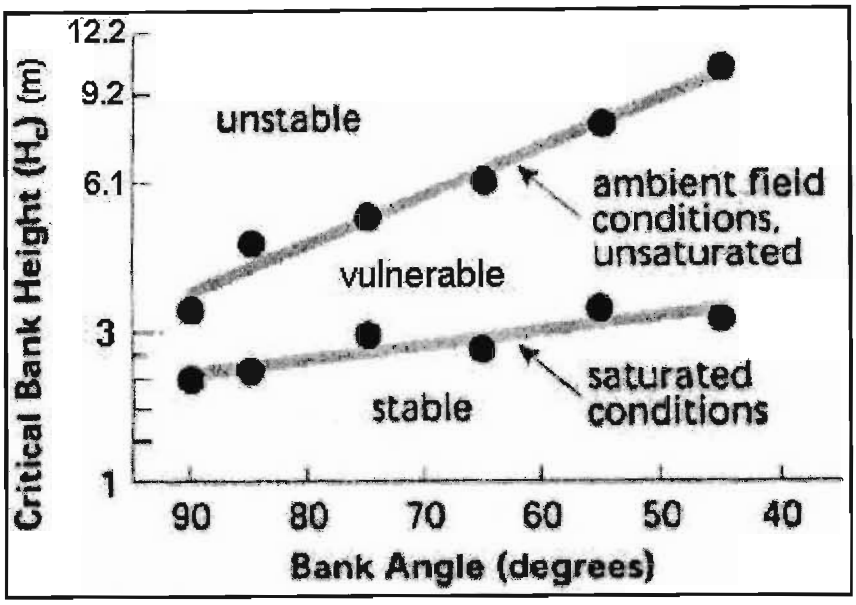


Figure 8: An example of a bank stability chart for estimating the critical bank height (H_c). (FISCRWG, 1998).

(ii) Other predictive approaches

Tools for forecasting bank erosion may be separated into two groups: those which estimate erosion primarily due to the movement of the water on the streambank surface and those which concentrate on subsurface geotechnical features (FISCRWG, 1998). Among the former is an index of streambank erodibility based on field inspections of emergency spillways (Moore *et al.,* 1994; Temple & Moore, 1997). Erosion is estimated for sites where a power number based on velocity, depth, and bend geometry exceeds an erodibility index computed from tabulated values of streambank material properties. Also among this group are analytical models such as the one developed by Odgaard (1989), which include sophisticated descriptions of flow fields, but call for input of an empirical constant to quantify soil and vegetation attributes. These models however, should be applied with careful consideration of their limitations. For example, Odgaard's (1989) model should not be employed to investigate bends with large curvature.

The second group of predictive tools concentrate on banks that undergo mass failure due to geotechnical processes. Side slopes of steep channels may be high and steep enough to be geotechnically unstable and therefore are prone to fail under the influence of gravity. Fluvial processes in such instances serve primarily to detach blocks of failed material from the bank toe, leading to a re-steepened bank profile and a new cycle of failure (Figure 9). The exploration of bank failure processes along incised channels has led to a method for relating bank geometry to stability for a given set of soil conditions (Osman & Thorne, 1988). If the banks of a suggested design are to be higher than about three metres, then stability analyses should be conducted, in consultation with a structural or civil engineer (Figure 9). Bank height assessments should enable scour to occur along the outside bends without jeopardising the entire design. High, steep banks are also prone to internal erosion, or piping, as well as streambanks of soils with high dispersion rates (FISCRWG, 1998).

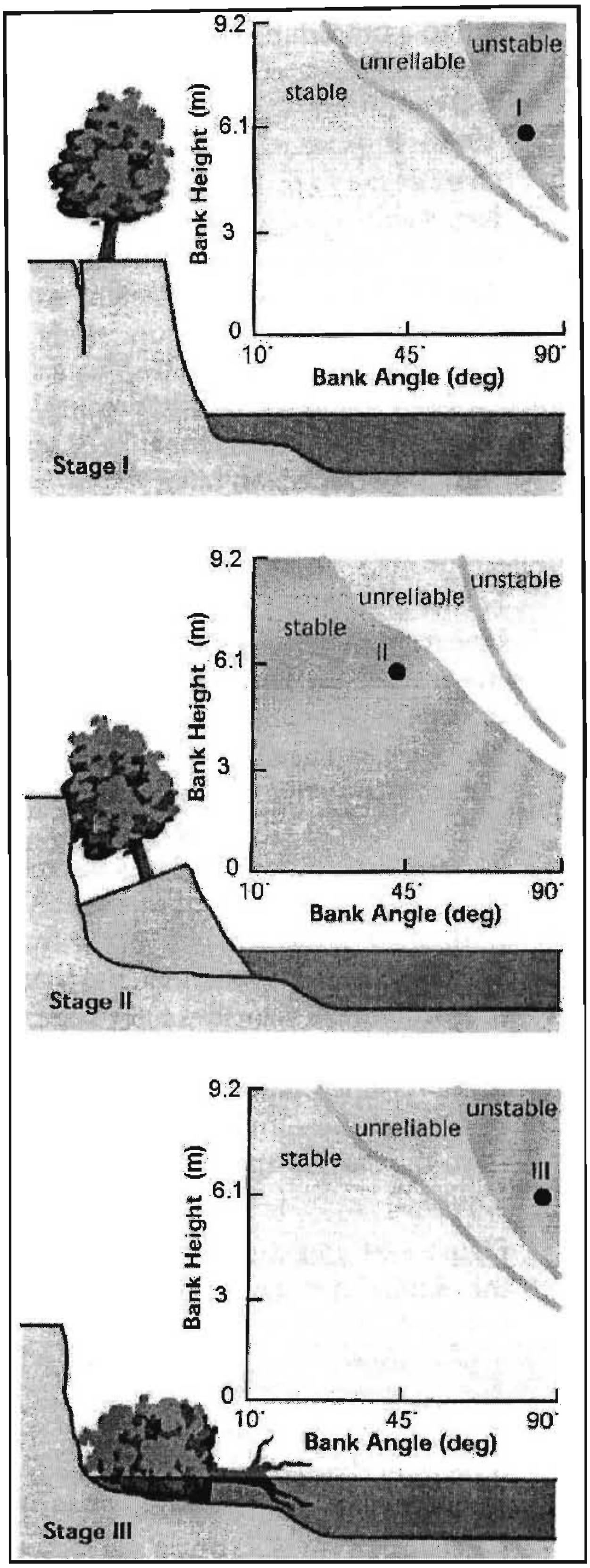


Figure 9: The stages of bank failure. Depending on the height, angle, and soil conditions of the bank profile, so will its stability vary from stable to unstable (FISCRWG, 1998).

(iii) Bank instability and its effect on channel widening

Bank height which increases beyond the critical conditions of the bank material often causes channel widening. Simon and Hupp (1992) show that there is a positive relationship between the amount of bed level lowering by degradation and the degree of channel widening. Dickinson and Scott (1979), cite bank recession rates, and channel widening, as functionally related to the inherent susceptibility of the bank material to erode, the nature of agricultural activity in the vicinity, and a characteristic associated with hydraulic shear forces. This is reiterated by Australia's Land and Water Resources Research and Development Corporation stating that activities such as the over-clearing of land, allowing of uncontrolled stock grazing along water courses, and the straightening of channels, disturb the equilibrium that exists between the flow regime and channel and are key causes of bank instability and channel widening (LWRRDC, 1998). The adjustment of channel width by mass-wasting procedures represents an important mechanism of channel modification and energy dissipation in alluvial streams, occurring at rates covering several orders of magnitude, of up to hundreds of metres per year (Simon, 1994). Present and future bank stability may be analysed using the following procedure:

- measurement of the current channel geometry and shear strength of the channel banks
- estimation of the future channel geometries and model worst-case pore pressure scenarios and average shear strength qualities

For fine-grained soils, cohesion and friction angel data can be obtained from standard laboratory testing (triaxial shear or unconfined compression tests) or by *in situ* testing with a bole-hole shear testing device (Handy & Fox, 1967; Luttenegger & Hallberg, 1981; Thorne, 1981; Thorne *et al.,* 1981; Simon & Hupp, 1992). For coarse-grained, cohesionless soils, estimates of friction angles can be obtained from reference manuals. By combining these data with estimates of future bed elevations, relative bank stability can be assessed using bank stability charts as discussed earlier.

(iv) Predictions of bank stability and channel width

Bank stability charts can be used to determine the following:

- the timing of the initiation of general bank instabilities (in the case of degradation and increasing bank heights)
- the timing of renewed bank stability (in the case of aggradation and decreasing bank heights)
- the bank height and angle needed for a stable bank configuration under a range of moisture conditions

Estimates of future channel widening can also be made using measured channel-width data over a period of years and then fitting a nonlinear function to the data (Figure 10). Williams and Wolman (1984) used a dimensionless hyperbolic function of the following form to estimate channel widening downstream from dams:

$$\frac{Wi}{Wt} = j1 + j2\left(\frac{1}{t}\right)$$

where:

- Wi = initial channel width (m)
- Wt = channel width at t years after Wi (m)
- t = time, in years ;
- $j1$ = intercept;
- $j2$ = slope of the fitted straight line on a plot of Wi/Wt versus $1/t$

Wilson and Turnipseed (1994) used a power function to describe widening after channelisation and to estimate future channel widening in the Loess area of Northern Mississippi:

$$W = xt^{d}$$

where:

- W = channel width (m)
- x = coefficient, determined by regression, indicative of the initial channel width
- t = time, in years
- d = coefficient, determined by regression, indicative of the rate of channel widening

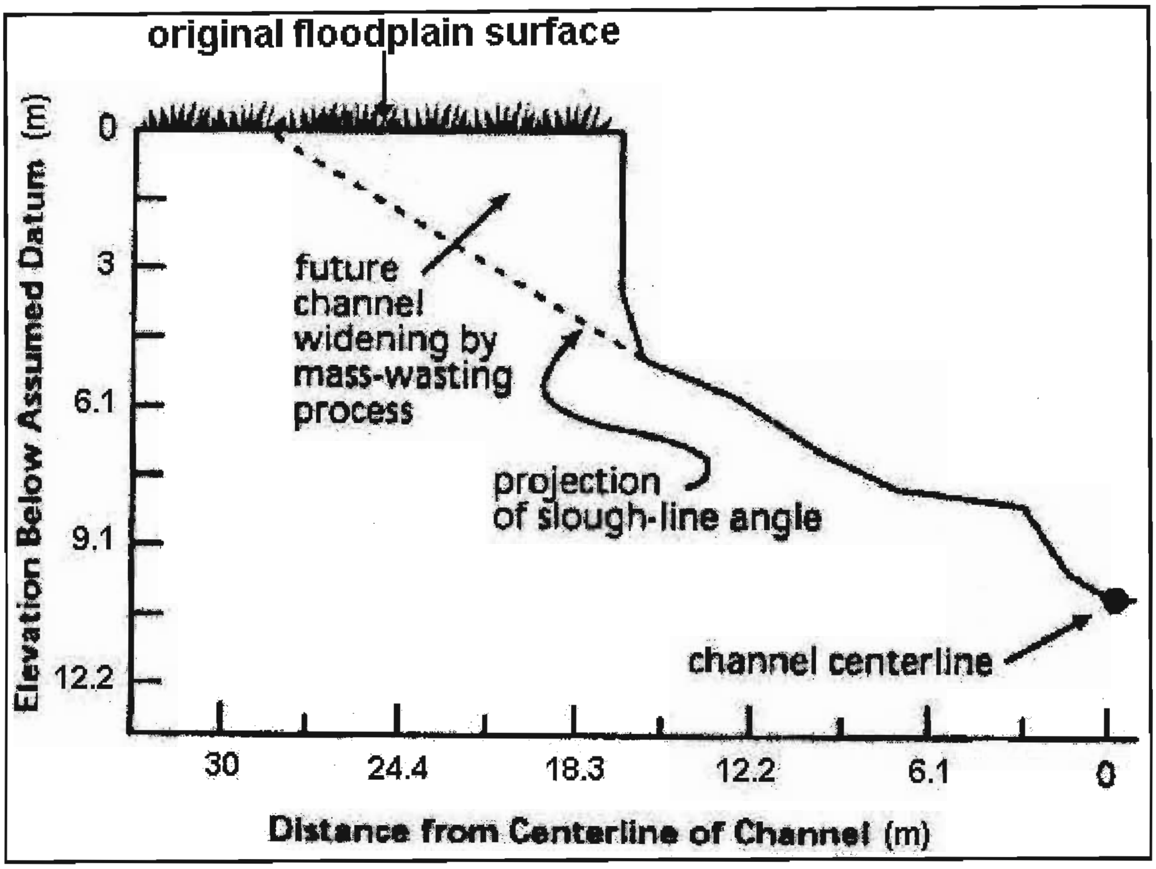


Figure 10: An example of a method to estimate the future channel widening for one side of the channel (FISCRWG, 1998).

2.1.5 Solutions to bank instability: techniques and approaches

(i) The importance of bed stability

Bed stability is an essential pre-requirement for bank stability, although systems carrying high, dynamic bedloads may still in some cases have stable banks. However, as it is not the focus of this research, bed stability will only be considered briefly in this document. Aggrading channels are liable to braid or exhibit hastened lateral migration in reaction to middle or point bar growth. Degrading channels widen explosively when bank heights and angles surpass a critical threshold specific to bank soil type. Bed aggradation can be confronted by stabilising eroding upstream channels containing erosion on the watershed, or installing sediment traps, containments (Haan *et al.*, 1994), or debris basins (U. S. Army Corpse of Engineers, 1989). If aggradation is primarily due to deposition of fine material, it can be addressed by narrowing the channel, although a narrower channel might require more bank stabilisation measures.

If bed degradation is occurring or is expected to occur, and if modification is planned, the rehabilitation initiative should include flow modification, grade control measures, or other strategies that lessen the energy gradient or the energy of flow (FISCRWG, 1998). There are many examples of grade control structures. The applicability of a particular version of structure to a specific rehabilitation event depends on a number of factors, such as hydrologic conditions, sediment size and loading, channel morphology, floodplain and valley characteristics, convenience of construction materials, ecological objectives, and time and funding constraints. Boulder clusters, for example, can be used to provide cover, create scour holes, or areas of reduced velocity for the protection of banks (Flosi & Reynolds, 1991; Sehhorn, 1992). Weirs or sills, which can be constructed out of material that is found in the vicinity such as logs, rocks, or quarry stone and placed across the channel and anchored to the streambank and/or bed can create pool habitat, control bed and bank erosion, or collect and retain gravel (Shields, 1983; Gore & Shields, 1995; Shields *et al.*, 1995). Grade control structure stilling basins can be useful habitats in severely degraded warm water streams (Cooper & Knight, 1987; Shields & Hoover, 1991). Newbury and Gaboury (1993) report the construction of artificial ripples that serve as bed degradation controls. Kern (1992) used “river bottom ramps” to control bed degradation in the River Danube meander rehabilitation initiative. Ferguson (1991) reviews innovative designs for grade control structures that enhance streamside habitat and anaesthetic effect. Neilson *et al.* (1991) provide a comprehensive review on grade control structures.

(ii) Approaches to bank stabilisation

Stream corridor rehabilitation may require that streambanks be temporarily (years to decades) stabilised while floodplain vegetation rejuvenates, even where streams preserve relatively natural patterns of flow and flooding. The intention in such instances should be to halt the accelerated erosion often identified with unvegetated banks, and to decrease erosion to rates appropriate to the stream system and setting. Under these conditions, the preliminary bank protection may be sustained exclusively with vegetation, wood and rock as required. In other cases, land development or adjusted flows may prescribe the use of hard structures to clinch permanent stream stability, and vegetation is used largely to address specific ecological inadequacies such as a lack of channel shading. In either case (permanent or temporary bank stabilisation), stream flow approximations are used to ascertain the degree to which vegetation must be augmented with more enduring materials (natural fabrics, wood, rock, etc.) to achieve appropriate stabilisation (FISCRWG, 1998).

Bank stabilisation may be required in restored channels due to floodplain land uses or because newly constructed banks are more susceptible to erosion than “seasoned” ones. However, if ecosystem rehabilitation is the objective, more than just bank stabilisation may be required. Floodplain plant communities owe their diversity to physical processes that include erosion and deposition attributed to lateral migration of the stream channel (Henderson, 1986). Bank erosion control techniques must be selected with the dominant (sub-aerial, scour, or slumping) erosion processes in mind (Shields & Aziz, 1992). This latter point is important and will play a significant role in the design of SR-DSS.

Stabilisation methods can generally be grouped into one of the following four categories: indirect methods, surface armour or hard techniques, vegetative methods, and those that specifically deal with correcting geotechnical instabilities. Indirect methods advance into the stream channel and redirect the flow so that hydraulic forces at the channel edge are eased to a non-erosive level. Indirect methods can be categorised as dykes (permeable and impermeable) and other flow deflectors such as bendway weirs, stream "barbs" and Iowa vanes. Tree revetments are also a common indirect method used in bank protection. This method involves a row of interconnected trees attached to the toe of the streambank or to deadmen in the streambank to decrease flow velocities along eroding streambanks, trap sediment, and supply a substrata for plant establishment and erosion control (Shields, 1983; Shields & Aziz, 1992).

Surface armour is a shielding material that is in direct contact with the streambank and can be categorised as stone, other self-adjusting armour (sacks, blocks, rubble, etc.), rigid armour (concrete, soil cement, grouted riprap, etc.) and flexible mattress (gabions, concrete blocks, etc.) For example, the stone toe protection method is a ridge of quarried rock or stream cobble situated at the toe of the streambank as an armour to divert flow from the bank, stabilise the slope, and encourage sediment deposition (King County WDPW, 1993; Du Poldt, 1996).

Vegetative methods can act as either armour or indirect protection and, in some applications, can behave as both. Vegetated gabions are an example of this. These consist of wire mesh rectangular baskets, filled with small to medium sized rocks and soil particles and threaded together to form a structural toe or sidewall. The structures are consolidated, and secured to the slope after live branch cuttings are placed on each successive layer between the rock filled baskets to take root (Henderson, 1986; USDA-NRCS,1996). Plantlings may be located on upper bank and floodplain areas by using conventional means of seeding or by planting bare root and container-grown plants. However, these tactics afford little initial defence to flows, and plantlings may be devastated if subjected to high water before they are adequately established. Cuttings, pole plantings, and live stakes chosen from species that sprout readily are more durable to erosion and can be used lower on the bank (Figure 11). Furthermore, cuttings and pole plantings can give immediate moderation of flow velocities if planted at high densities (Thompson & Green, 1994; USDA-NRCS,1995a). Often, they can be placed deep enough to sustain contact with enough soil moisture levels, thereby eliminating the need for irrigation (USEPA, 1993; King County WDPW, 1993). The dependable sprouting properties, hasty growth, and general availability of cuttings makes them particularly attractive for use in bank revegetation projects, and they are used in most of the integrated bank protection approaches described here and in the techniques made available in SR-DSS. A section on planting and stabilising techniques will be included later in this Chapter.

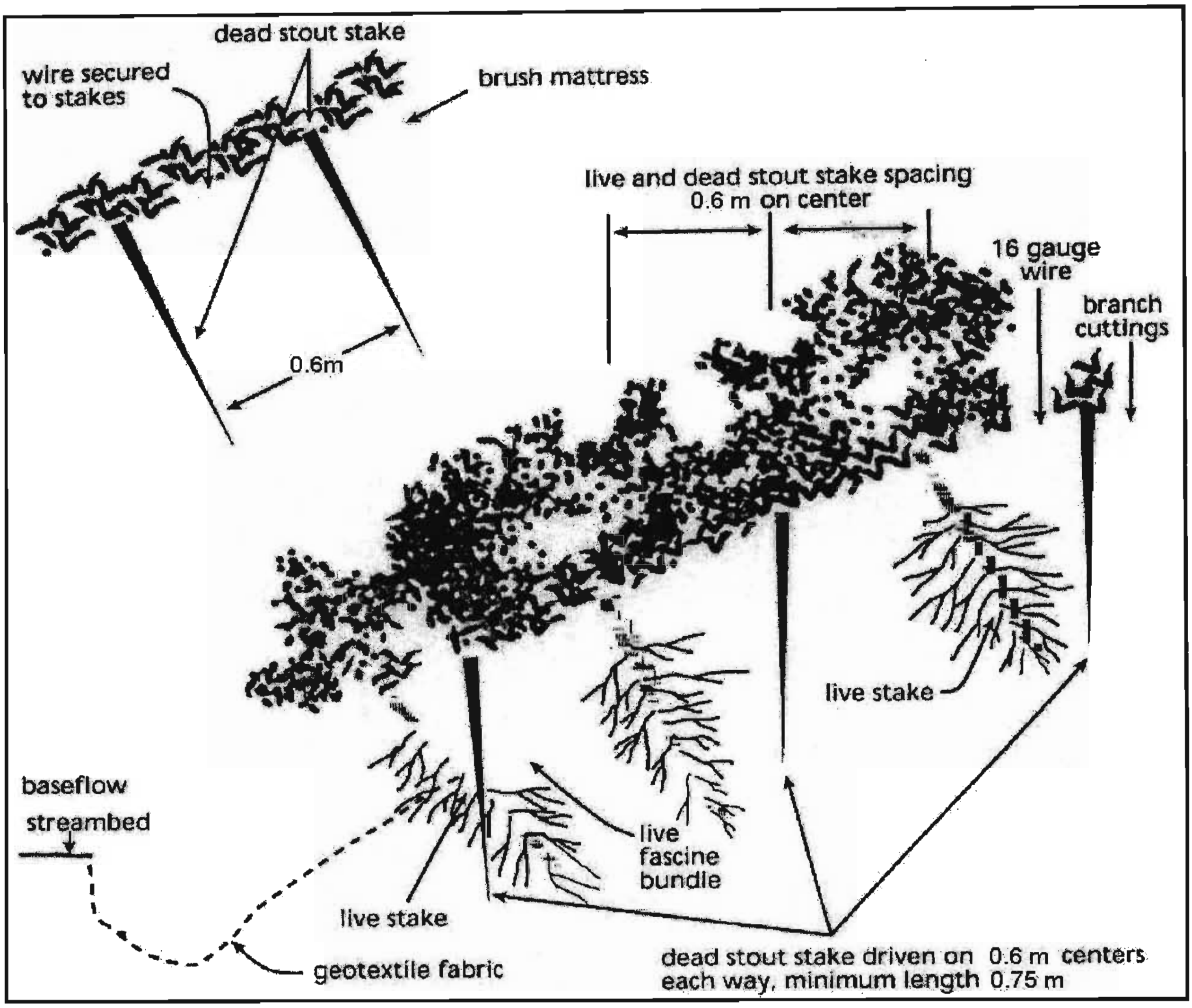


Figure 11: Cutting systems. Specification of the brush mattress method (USDA-NRCS, 1996).

The fourth category of stabilising methods is composed of techniques to correct problems prompted by geotechnical instabilities, such as the bank shaping and planting method (Gray & Leiser, 1893; USDA-NRCS, 1995b). This method involves the regrading of streambanks to a stable slope, placing topsoil and other materials required for sustaining plant growth, and selecting, installing, and establishing appropriate plant species.

It has already been said that newly constructed channels are more vulnerable to bank erosion than older existing ones, with similar inflows and geometries, due to the influence of vegetation, armouring , and the seasoning effect of clay deposition on the banks of older channels (Chow, 1959). In most cases, outer banks of restored or newly constructed meanders will need protection. Structural methods are required (Thomas *et al.*, 1995) if effective stability is demanded, but these may include living components, such as described above. If time permits, the new channel may be constructed "in the dry" and banks established with woody vegetation.

After allowing the vegetation several growing seasons to establish, the flow may be deflected in from the existing channel (FISCRWG, 1998).

It is widely understood that the causes of extreme erosion may be reversible through alterations in land use, livestock management, floodplain rehabilitation, or water management (Platts, 1979, 1989; Smith & Prichard, 1992; Schueler, 1996; Riley, 1998). In some cases, even ordinary rates of bank erosion and channel movement may be regarded as unacceptable due to adjacent development, and vegetation might be used predominately to retrieve some habitat functions in the vicinity of hard bank stabilisation measures. In either case, the considerations discussed above with respect to soils and the use of indigenous plant species, etc., are pertinent within the bank zone. A set of specialised methods can be implemented to help ensure plant establishment and develop enhanced habitat conditions. Bioengineering is the integration of vegetative cuttings, which are used independently or in combination with other natural materials to control streambank erosion. Soil bioengineering bank stabilisation systems have not been utilised for general employment under certain flow conditions. The choice as to whether and how to use them requires careful attention of a collection of factors. On larger streambanks where erosion is formidable, a convincing approach involves a team effort that incorporates expertise in soils, biology, plant sciences, landscape architecture, geology, engineering and hydrology. Soil bioengineering strategies normally exploit plant materials in the form of live woody cuttings or poles of quickly sprouting species, which are inserted deep into the bank profile or anchored in several other ways. This serves the dual purpose of enduring the washout of plants during the early establishment period, while affording some rapid erosion defence due to the physical counteraction of the stems. Plant materials alone are sufficient on some streams or streambank zones, but as erosive forces escalate, they can be united with other materials such as logs, rocks or brush, and natural fabrics. In some cases, woody debris is included specifically to improve habitat characteristics of the bank and near bank channel zones.

Preparatory site examinations and engineering analyses should be performed, as outlined above, to determine the method of bank failure and the viability of using vegetation as an element of the proposed bank stabilisation work. In addition to the technical examinations of flows and soils, preliminary analyses must give consideration to site access, maintenance, urgency and convenience of materials.

Any specific site must be examined to ascertain how vegetation can or cannot be used. Soil cohesiveness, the presence of gravel lenses, frost, the quantity of sunlight contacting the bank, and the ability to ensure that grazing will be prevented or managed are all considerations in appraising the suitability of vegetation to accomplish bank stabilisation. In addition, adjusted flow patterns may make segments of the bank inhospitable to plants because of unsuitable timing of inundation rather than flow velocities and durations (Klimas, 1987). The need to extend protection well beyond the primary focus of erosion and to protect against flanking is a significant design consideration (FISCRWG, 1998).

(iii) Planting and stabilisation techniques

Plant establishment techniques vary depending on site and species characteristics. Poles, or cuttings of species that sprout readily, and planting them to depths that will ensure contact with moist soil during the dry season are commonly used in arid regions. In arid regions, or where the watertable is deep underground, deep auguring and temporary irrigation is sometimes used to establish cuttings, rooted and/or container grown plants (Thorne 1990). In areas where water is readily available, container plants are commonly used, particularly for those species which do not readily sprout from cuttings. Other methods have been used to various degrees of success, however, local experience and knowledge should be sought to determine the most reliable and efficient plant establishment approaches for particular areas and species, and to determine what problems to expect. Literature is available on South African indigenous flora, for example, the Water Research Commission in partnership with the South African Wattle Growers Association, developed an indigenous species database assisting in the choice of appropriate species in rehabilitation exercises (Kellner *et al.,2000).* Quinn and Catherine (pers. Comm.,2001) are in the process of developing a database assisting specifically in the selection of riparian species in the seven South African biomes.

It is important to protect plantlings from livestock and other herbivores. Species that are less palatable are also a viable option. A study done by Schoeman (1999) revealed that the use of unpalatable species (*Melinis nerviglumis* and *Hyparrhenia dregeana*) greatly increase the establishment and survival rate of plantlings. The use of exclusion cages also increased the survival rate to nearly 100% despite severe drought conditions experienced that year.

In southern Africa, riparian areas are dominated by mixed stands of species. The emphasis therefore, should be to emulate natural patterns of colonisation by staggering the planting program over a period of years to ensure structural variation. Species from all the structural components (Over storey, Under storey, Ground cover and Marginal cover) should be included, particularly if they are required to meet specific objectives such as erosion control.

(a) Anchored cutting systems

Various techniques are available that use extensive numbers of cuttings organised in layers or bundles, which can be fastened to streambanks and partially buried material. Depending on how these systems are organised, they can provide direct protection from erosive flows, obstruct erosion forces from up slope water origins, promote trapping of sediments, and quickly develop dense roots and sprouts. Brush mattresses and woven mats (USEPA, 1993; Thompson & Green, 1994) are commonly used on the bank face and consist of cuttings laid side by side and interwoven or secured with jute cord or wire which is held in place by stakes. Brush layers are cuttings laid on terraces dug into the bank, then buried so that the branch ends advance from it. Fascines or wattles (Gray & Leiser, 1983; USDA-NRCS, 1995a) are bundles of cuttings fastened together, placed in shallow trenches arranged horizontally on the bank face, partly buried, and staked in place. A similar system, called a reed roll, uses partially buried and staked burlap rolls filled with soil and root material, or rooted shoots, to establish herbaceous species in appropriate habitats. Anchored bundles of live cuttings also have been installed perpendicular to the channel on newly assembled gravel floodplain areas to decrease floodwater energy and encourage deposition of sediment (Karle & Densmore, 1994).

(b) Geotextile systems

Geotextiles have been used for erosion regulation on road embankments and similar upland settings, generally in association with seeding, or with plants placed through silts in the fabric (Thompson & green 1994; USDA-NRCS. 1996). In self-sustaining streambank applications, only natural, biodegradable materials should be used, such as jute or coconut fibre (Johnson & Stypula, 1993). The common streambank use for these materials is in the erection of vegetated geogrids, which are similar to brush layers except that the fill soils between the layers of cuttings are enveloped in fabric allowing the bank to be constructed in consecutive "lifts" of soil, interchanging with brush layers. This technique permits reconstruction of a bank and contributes significant erosion resistance (Figure 12). Natural fibres are also used in "fibre shines", which are sold specifically for streambank applications. These are cylindrical fibre bundles that can be staked to a bank with cuttings of rooted plants embedded through or into the material. Vegetated plastic geogrids and other non-degradable fabrics can be employed where geotechnical difficulties demand drainage or supplementary strength.

(c) Trees and logs

Tree revetments are made from entire tree trunks rested parallel to the bank and wired to piles or deadman anchors (Flosi & Reynolds, 1991; King County WDPW, 1993). The flexible branches of trees provide obstacles to flow, and ensnare sediment. The primary objective to these systems is the use of extensive qualities of wire to decrease the potential for trees to become detached and cause downstream damage.

Several projects have successfully used large trees in combination with stone to provide bank protection as well as improved aquatic habitat. Large logs with intact root wads are placed in trenches cut into the streambank, such that the root wads advance beyond the bank face at the toe (Figure 13). The logs are overlapped and/or strengthened with stone to ensure stability and the extending root wads effectively decrease flow velocities over a range of flow elevations (Flosi & Reynolds, 1991;USDA-NRCS, 1996). An essential advantage of this strategy is that it re-establishes one of the natural roles of large woody debris in streams by generating a dynamic near-bank environment that traps organic material and maintains colonisation substrates for invertebrates and sanctuary habitats for fish. The logs eventually rot, developing into a more natural bank. The revetment stabilises the bank until woody vegetation has matured, at which time the channel can reciprocate to a more natural pattern.

In most cases, bank stabilisation projects use mixtures of the methods described above in an integrated approach. Toe protection often requires the use of stone, but quantities can be greatly decreased if large logs can also be utilised. Similarly, stone blankets on the bank face can be substituted with geogrids or supplemented with interstitial plantings. The majority of upper bank areas can generally be stabilised utilising vegetation alone, albeit anchoring systems might still be required (FISCRWG, 1998).

(d) Integrated systems

A leading concern with the use of structural approaches to streambank stabilisation is the lack of vegetation in the zone immediately adjoining the water. Notwithstanding a long-standing concern that vegetation destabilises stone revetments, there has been little supporting evidence and even some evidence to the contrary (Thorne, 1990; Sheilds, 1991). Presuming that the loss of conveyance is accounted for, the addition of vegetation to structures should be contemplated. This can involve establishment of cuttings duringconstruction, or insertion of cuttings and poles between stones on presenting structures. Live cribwalls (Shileds & Aziz, 1992; King County WDPW, 1993) may be assembled with cuttings or rooted plants extending through the timbers from the backfill soils. Vegetated gabions (Henderson, 1986; Flosi & Reynolds, 1991) may be constructed in a similar manner. These methods provide an alternative to using hard engineering techniques.

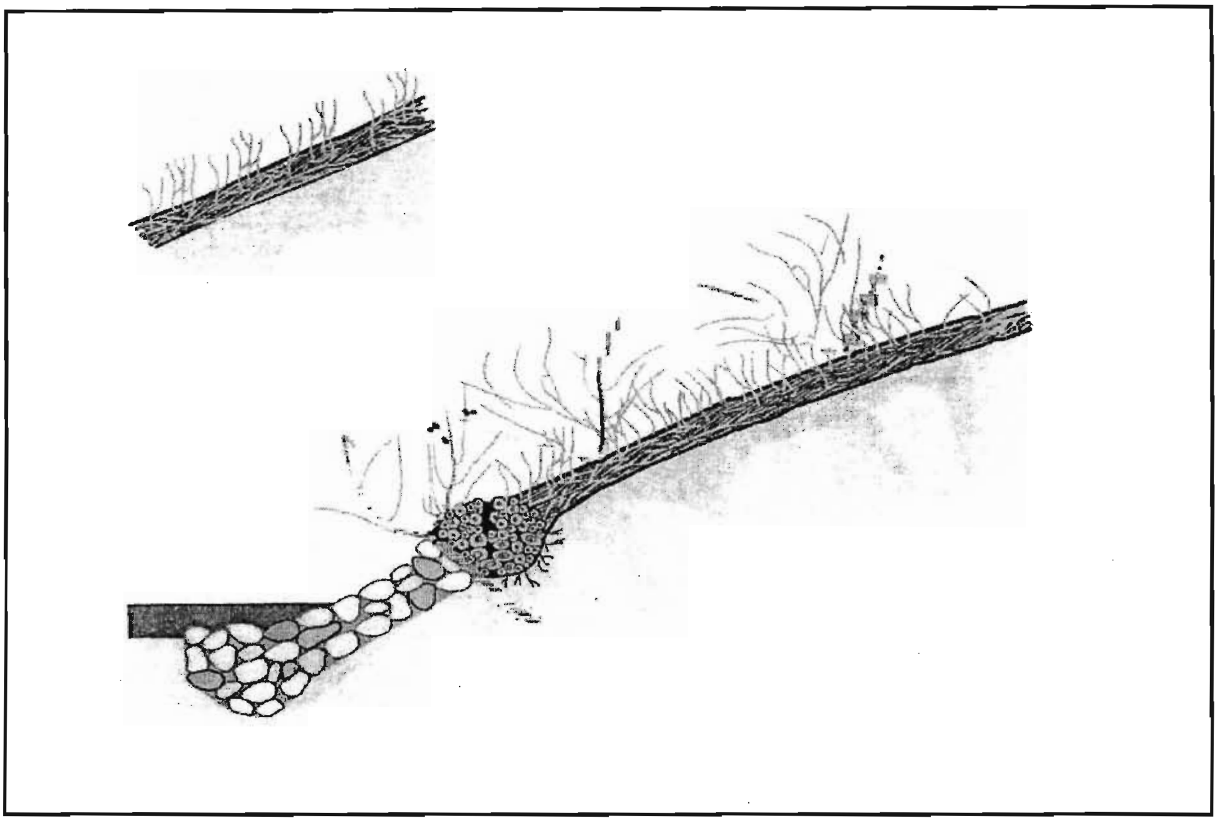


Figure 12. Geotextile systems. Used for erosion control on embankments usually in combination with seeds, or seedlings (FISCRWG, 1998).

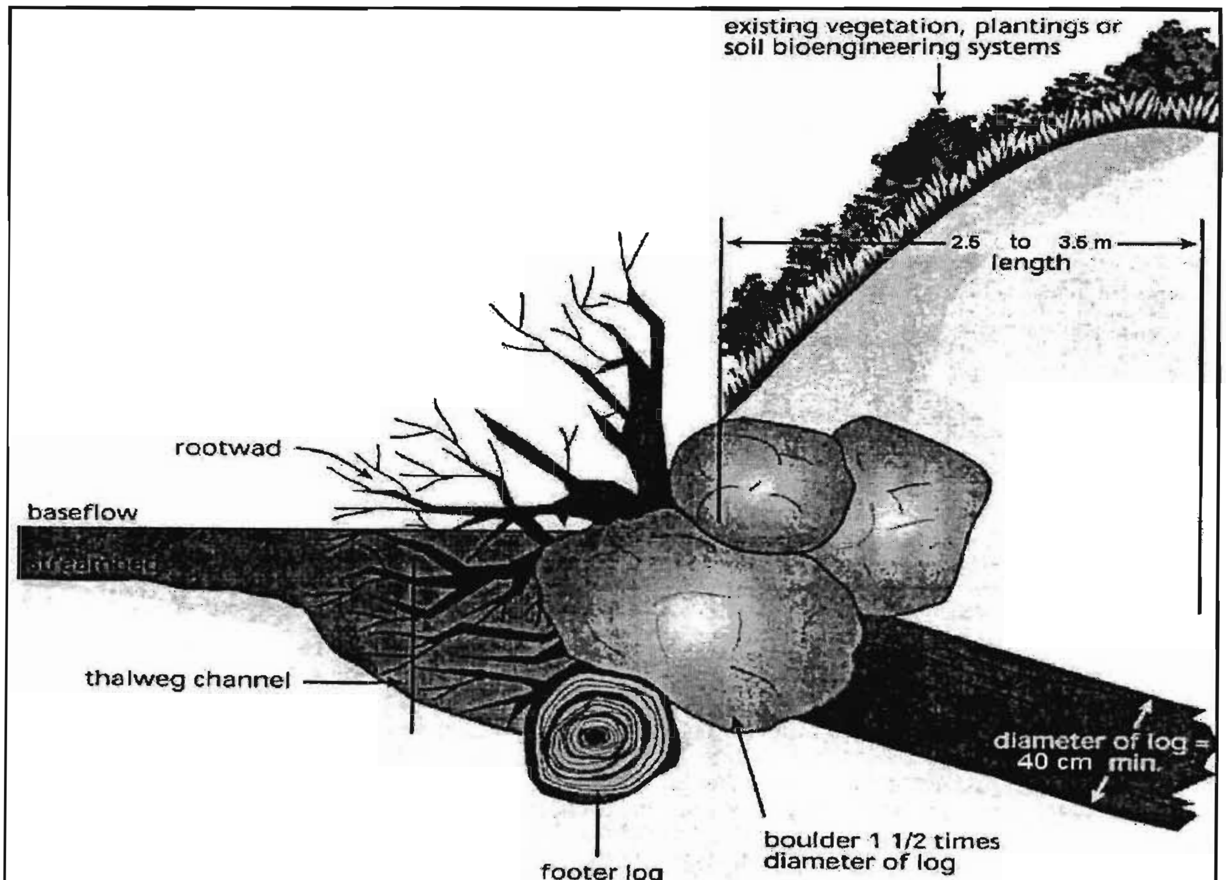


Figure 13. Revetment systems. Specifications of the rootwad and boulder technique (USDA-NRCS, 1996).

(iv) Technique effectiveness and success

The intrinsic properties of a given bank stability strategy, and the physical characteristics of a suggested site, affect the suitability of that technique for that site. Numerous techniques can be devised to satisfactorily decipher a specific bank stability problem by resisting erosive forces and geotechnical failures. The challenge is to recognise which technique provides protection against the strength of the attack and therefore functions most effectively when tested by the strongest process of erosion and most critical mechanism of failure. Environmental and economic factors are included in the selection procedure, generally making soil bioengineering methods very appealing. The adopted outcome however, must first fulfil the requirement of being effective as bank stabilisation; otherwise, environmental and economic aspects will be irrelevant. Soil bioengineering may be a valuable tool in controlling streambank erosion, but it should not be considered a cure-all. It must be performed in a logical manner by personnel experienced in the channel processes, the ecology, and streambank stabilisation techniques.

An important consideration for almost all rehabilitation work is the risk of rehabilitated channel being damaged or destroyed by erosion or deposition. Designers of rehabilitated streambanks are challenged with significant levels of uncertainty. In some cases, it may be advisable for designers to estimate risk of failure by calculating the joint probability of design assumptions being false, design equations being false, design equation inaccuracy, and/or the occurrence of excessive hydrologic events during project life. Good design practice also requires investigating channel performance at discharges well above and below the design condition, strategies for which are available and are an important part (FISCRWG, 1998).

2.2 Bank Stability and vegetation

2.2.1 The role of vegetation in bank and stream ecosystem rehabilitation

Although some authors debate the most suitable vegetation type for bank stability, all are in agreement that vegetation, as opposed to no vegetation substantially improves the stability of streambanks with respect to fluvial entrainment and mass movement (Carson & Kirby, 1972; Hickin, 1974; Kirby & Morgan, 1980; Bowie, 1982; Murgatroyd & Ternan, 1983; Thorne, 1990; Beeson & Doyle, 1996; Trimble, 1997; Harmel *et al.*, 1999; LWRRDC, 1999a, b). Some authors argue that grassed banks retain more sediment than forested reaches [about 2100m^3 to 8800m^3 more sediment (Trimble, 1997)]. This suggests that where erosion control is needed, as opposed to mitigating against mass collapse, grass and matt type plant species should be considered over trees and deep rooted species (Murgatroyd & Ternan, 1983; Trimble, 1997). Research done by Hamel *et al.* (1999), on the other hand, suggests vegetation provides increased bank stability, brought about by the support provided by the deep roots, and hence could be used to mitigate against sloughing and degrading streambanks. In addition to this, research by Bowie (1982) suggests that indigenous species are superior to exotic species in their ability to resist bank instability and erosion. Vegetation can significantly affect the dynamics of any particular riverbank (Gray, 1978; Gray & Leiser, 1983; Gray & MacDonald, 1989; Thorne, 1990). It is convenient to consider these effects separately, while bearing in mind that these processes are part of a whole real world. These effects have important and far-reaching implications for the use of vegetation in schemes focussing on the protection and stabilisation of streambanks.

Vegetation not only pays a pivotal role in bank stability, but also in the ecosystem of the bank. It is further argued, that restoring the vegetation to its pre-degradation condition, should be the ultimate goal. Protecting the bank simply by planting exotics will not suffice. Better protection will be given by the plants and the structure that has adapted to local condition, as the research of Bowie (1982) suggests. Habitat, conduit, filter/barrier, source and sink functions depend to a large extent on biomass amount and condition. Rehabilitation designs should protect existing indigenous vegetation and restore vegetative structure to result in a contiguous and connected stream corridor. Vegetation can be used as a tool to achieve specific objectives in streambank condition however, the current trend in rehabilitation is to apply a multi-species or ecosystem approach (FISCRWG, 1998). In addition, the following functions are performed by riparian vegetation, which are essential to ecosystem performance (United States Army Corps of Engineers, 1991; Veneman, 1994; Bren *et al.*, 1997; Klapproth, 1999). Riparian Vegetation:

- Provides shade that reduces the temperature of the water
- Encourages the deposition of sediments and other contaminants
- Reduces the nutrient loads of streams
- Provides structural support to streambanks
- Reduces erosion caused by uncontrolled runoff
- Provides riparian wildlife habitat
- Protects fish habitat
- Maintains aquatic food webs
- Provides an aesthetically appealing greenbelt
- Provides recreational opportunities
- Is a source of medicinal products

Clear evidence that vegetation can be used for protecting riverbanks against erosion and stabilising them with respect to mass failure has been demonstrated, however, there is disagreement as to its practical usefulness in this regard. For example, work done by the U.S. Army Corps of Engineers (1978), showed that vegetation is an important part of a rehabilitation scheme. However, U.S. Army Corps manuals that use riprap exclude the vegetation at the construction phase, and require that invasives be subsequently removed for the following reasons. Firstly, the stems of the vegetation might cause local scour in the wake zone.

Secondly, growth of the vegetation might disrupt the riprap blanket. Thirdly, dead roots leave voids and cause areas of weakness that may lead to piping (Hagerty, 1991). Fourthly, vegetation obscures vision, which makes the annual inspection to check the integrity of the riprap difficult. Although these are valid arguments, an important point has been missed. These difficulties do not apply equally to all species. Furthermore, when the advantages of vegetation presence are weighed against the disadvantages, it is believed that the benefits far outweigh the weaknesses.

Vegetation may not be the absolute remedy in all rehabilitation work though. In many cases it is necessary to fix the toe of the bank using hard or engineering structures. However, at times it is not necessary to carry this structural protection up to the top of the bank. In fact, Thorne (1990) suggests that minimum toe protection and bank grading may be all that is required structurally, and indigenous coloniser species planted at the top of the bank should provide sufficient protection in many cases. This approach has been found to be compatible with sound engineering practices, while comparing favourably with more traditional alternatives aesthetically, environmentally and economically (U.S. Army Corps of Engineers, 1984). The ideal riparian vegetation structure on the other hand should include all the components described below, unless site specific conditions discourage the inclusion of a certain component.

2.2.2 The structure of riparian forest

Part of the criteria for a healthy riparian forest structure, as exhibited by good riparian vegetation[1] is one that has all the structural components. These are the over storey, under storey, ground cover, and marginal cover, as defined by its size, position on the bank, and its strength. The components represented on the bank can have a large influence in bank stability. Abernethy and Rutherford (1999) describe these structural components, a summarised version of which is presented below.

(i) Over storey

The over storey usually consists of trees ranging from about 5 metres to 20 metres in height, depending on the species composition and local environmental conditions. This component is very heavy, and can affect the stability of the bank in the form of surcharge, as already indicated. The root systems of trees are variable, but they usually decrease rapidly in density and surface area away from the trunk and with depth. The root system usually consists of a root ball, or plate, and has a diameter of about 5 times that of the trunk of the tree, which then decreases rapidly beyond that. There are usually very few roots beyond the edge of the tree canopy, and below 1 to 1.5 metres in depth. The root ball of terrestrial plants also grow parallel to the soil

1 Refer to glossary provided

surface and never extend beyond the water table. This means that shallow root systems exist where there is a high water table. A shallow root system can also indicate the presence of an impermeable stratum close to the surface of the soil.

(ii) Under storey

The under storey is usually 1 to 1.5 metres in height and consists of a complex array of shrub species and little trees. The rooting depth is less than that of the over storey but may still be more than 1 metre in depth. The root system does not extend beyond the canopy, as with trees, and depth and density diminishes with distance from the trunk. The effect of weight or wind on bank stability is minimal.

(iii) Ground cover

This segment of the vegetation is usually less than 1 metre high and consists of sedges, grasses, prostrate shrubs, and forbs. They establish rapidly on the bank face, but are prone to trampling and grazing pressures. They will also not grow on vertical surfaces or below the low-flow water line. They do however, provide considerable reinforcement to a depth of about 0.3 metres by densely covering the bank surface and they also have a dense root mat.

(iv) Marginal cover

Marginal cover consist of some species of sedges, rushes (e.g. *Typha capensis)* and reeds (e.g. *Phragmites australis)*, which grow on the margins of the average water level, but will generally not survive for long periods of time in water which is more than 0.5 metres deep. They flourish in areas where terrestrial plants do not establish and in conditions of low water velocity (about 0.2m/s).

Now that the importance and the structure of the vegetation has been discussed, the emphasis will move onto the physical processes associated with the bank and how the vegetation growing on it minimises erosion.

2.2.3 Factors affecting bank stability

(i) Retardence of near bank flow

Vegetation decreases the boundary shear stress by increasing the effective roughness height of the boundary, thus increasing the flow resistance and displacing the zero plane of gravity upwards. A reduction in the velocity of flow initiates a reduction in the forces that cause erosion (Kouwen, 1970; Kouwen & Unny, 1973; Kouwen & Li, 1979; Kouwen *et al.*, 1980).

A further effect of bank vegetation is to reduce turbulence. Entrainment and detachment usually takes place during turbulent sweeps when velocities and stresses are very high. Vegetation can reduce the magnitude of instantaneous velocity and shear stress peaks by suppressing turbulence and so reduces erosion (Thorne, 1990).

Type of vegetation is another important variable. Grasses and shrubs are effective at low velocities, their mitigatory effect decreases as velocity increases. Trees and other deep rooted plants on the other hand are effective at high velocities. In this regard, the spacing of vegetation is an important factor too. Single, or small clumps of trees are obstacles to the flow that generates large-scale turbulence and severe bank attack in their wakes. Hence, the flow is usually able to isolate and flank hard points in the bank resulting from widely spaced trees or groups of trees. For trees to be effective in reducing flow attack, they must be spaced sufficiently closely that the wake zone for one tree extends to the next tree downstream, obstructing re-attachment of the flow boundary to the bank. The effects of trees continue to be important even after the death of the plant. A dense accumulation of downed timber on the bank of a stream can provide a considerable amount of protection from flow scour, however an isolated tree can generate local scour and become a locus of serious channel instability (Murgatroyd & Ternan, 1983; Thorne, 1990; Harmel *et al.,1999)*

(ii) Reduction in soil erodibility

Compared to unvegetated streambanks, those with a healthy stand of vegetation experience a greater resistance to erosion (Carson & Kirby, 1972; Hickin, 1974; Kirby & Morgan, 1980; Bowie, 1982; Murgatroyd & Ternan, 1983; Thorne, 1990; Beeson & Doyle, 1996; Trimble, 1997; Harmel *et al.*, 1999). The roots of plants not only bind the soil but also provide extra cohesion over and above any intrinsic cohesion that the bank material might have. The roots are effective in reducing processes which may weaken and loosen particles of soil. Furthermore, vegetation obstructs the flow of water across the streambank making the process less violent. This increases the infiltration rate for a precipitation event, decreasing the volume of runoff and reducing its effectiveness in generating surface erosion.

Generally, the use of species with a dense network of fibrous roots is preferable to one with a sparse network of woody roots. Fibrous roots provide a higher surface area and therefore bind the soil more effectively through more contact. Woody roots may disturb the structure of the soil and weaken it through root wedging, although research done by Gray (1978) suggests that this is at most a second order effect.

For effective protection, vegetation should extend down the bank, at least to the average low water plane, otherwise undercutting will occur where the root zone no longer reinforces the soil, and mass slumping will result. For this purpose, plants that are tolerant to inundation are better equipped. Thorne (1990) proposes that a mixture of terrestrial and riparian species and high water tables provide the best solution to combat bank erosion.

Where banks have become exposed and lack suitable cover, quick growing species are better able to respond to erosion events and recolonise eroded areas of bank than slow growing species. Slow maturing plants have a higher probability of being washed out and attacked if the time for them to become established is longer than the return period for flows that significantly erode the bank. The use of annual species will provide no protection to the bank during the period when they die back, which may well be the period of most significant bank erosion (Thorne, 1990). For instance, the Cape Province of South Africa has its rainy season during winter, a time when most annual species die back. Nevertheless, they may serve as an interim measure while perennial species establish.

(iii) Bank drainage

Compared with unvegetated banks, vegetated banks are drier and much better drained. Both of these points contribute enormously to bank stability because the bulk unit weight of the soil is low while effective and apparent cohesions increase. Vegetated banks, in general, are drier for three major reasons. Firstly, 15% to 30% of precipitation is prevented by vegetation from ever reaching the soil surface by intercepting it and re-evaporating it into the atmosphere. Secondly, soil moisture is significantly reduced between precipitation events through transpiration. Thirdly, suction pressures in the soil are increased and water is drawn towards the surface from greater depths than in an unvegetated bank. Decreasing the magnitude of positive pore pressures that often trigger failure following rapid drawn-down, vegetation can make a major contribution to bank stability (Thorne, 1990).

(iv) Soil reinforcement

A soil-root matrix produces a type of reinforced earth, which is much stronger than the soil or roots separately. Roots add tensile strength to the soil and through their elasticity, distribute stresses through the soil, and so avoid local stress build-ups and progressive failures. This reinforcement extends only down to the rooting depth of the vegetation. It is therefore important to include species which would ensure a mixed rooting depth (Thorne, 1990). Bank height is also an important factor to consider. If the bank height is less than or equal to the rooting depth, then roots almost certainly cross the potential shear surface and reinforce it against failure. Where the opposite occurs, slip surfaces for toe failures will pass beneath the zone of root reinforcement (Thorne, 1990). Shallow slips will continue to be prevented by root reinforcement binding the failure block together during and after collapse; so that failed blocks are more likely to remain at the toe and protect the intact bank from further erosion. The stabilising effect of root reinforcement on deep-seated failures however, will be lost (Gray & Macdonald, 1989). Banks of streams that are subject to severe degradation are clearly demonstrated by this phenomenon. In response to increasing bank heights and angles caused by basal lowering and toe erosion, trees switch from holding banks up to dragging them down (Simon & Hupp,1986; Harvey & Watson, 1986).

(v) Slope buttressing and soil arching

Buttressing at the toe of the slope helps retain it and loads the toe against shear failure. Arching occurs when soil is prevented from sliding between or around piles that are firmly anchored in an underlying and unyielding layer. A well rooted and closely spaced stand of trees extending along the bank toe achieves effective buttressing and arching of a riverbank, increasing its stability with respect to shallow and deep seated slips, and soil creep (Wang & Yen, 1974; Gray, 1978).

(vi) Surcharging

The weight of vegetation acting on the streambank is known as surcharging. Surcharging is often seen as detrimental to bank stability by most river engineers as sections of the bank-line are dragged down by the weight of overhanging trees. However, surcharging can also be beneficial to bank stability which depends on the slope, angle and position of the tree on the bank. The contribution of surcharge weight to the downslope component of weight on gently sloping banks is small compared with that of the slope-normal component. Consequently, surcharging decreases stability (Thorne, 1990). Trees at the top of steep banks present a major liability with respect to surcharging. Their weight tends to produce a shear force and a rotating movement that are highly effective in promoting toppling failure. This is especially pronounced when bank-top trees lean over into the channel as a result of asymmetry due to grazing only on the bankward side, or to wing loading (Thorne, 1990). These problems are strongly associated with bands of trees only 1 or 2 deep and hence a wide band of trees is preferable in terms of their impact on bank stability through surcharge.

(vii) Bank accretion

Bank accretion results when sediment deposition occurs around the basal area of plants. Research suggests that vegetation plays a major role in promoting sediment deposition on advancing banks (Harvey & Watson, 1986). These in turn promote lush growth due to their fertility further stabilising the bank, which in turn encourages more deposition. Bank accretion happens for two reasons (Thorne, 1990). Firstly, more vegetation retards the flow of water even further, allowing sediment to settle. Secondly, sediment carried as wash-load, which takes a very long time to settle by gravity is trapped by vegetation. This very fine sediment usually only settles once the water, which carries it, becomes stagnant. Research, done by Harvey and Watson (1986), suggests that wash-load sediment can be a significant factor on vegetated banks.

2.2.4 Other considerations

(i) Reference sections

Examination of a reference stream corridor, is often the best way to develop information on plant community composition and distribution. Once reference plant communities have been defined, design can begin to detail the measures required to restore those communities, and information is made available on suitable species for use in bank stabilisation techniques. When attempting to restore riparian vegetation, FISCRWG (1998) indicate that it is rarely feasible or desirable to plant the full complement of species represented on a reference site. The indication is that the dominant species, or those unlikely to colonise the site readily, should rather be planted, if these complement the stability of the bank.

(ii) Riparian zone width

Although the value of riparian buffer strips is well recognised, criteria for their sizing is variable and depends largely on the objective at hand. U.S. Army Corps of Engineers (1991) suggest that strips 30 metres wide may be adequate to sustain many of the functions listed above. Minimum widths for birds breeding on Iowa streams for example, range from between 12 metres to 210 metres (Stauffer & Best, 1980). Abernethy and Rutherfurd (1999), based on research conducted in Australia, determined a formula for required minimum buffer width for bank stabilisation. They maintain that it should not be less than 5 metres measured onto the floodplain from the bank crest. As banks become higher they become less stable. Hence, in addition to the 5 metres, it is recommended that riparian strips must also include a width component that compensates for bank height. The height allowance, as they call it, should not be less than the height of the bank measured vertically from the toe to the bank crest. Since stream stability is the most important criterion, the recommendation of Abernethey and Rutherfurd (1999) is echoed in this document. It must be noted that sustainable bank stability is the focus of this research and is required before any of the buffer functions mentioned above can be considered. Once this has been achieved, the buffer strip can be suitably widened to attain any goal or objective the user has in mind.

(iii) Connectivity and gaps

Stream corridor rehabilitation should maximise connections between ecosystem functions such as habitat, conduit, and filter or barrier processes. Rehabilitation designs should ideally enhance connections to existing or potential features such as vacant or abandoned land, rare habitat or wetlands, diverse or unique vegetative communities, springs, movement corridors for fauna and flora, and associated stream systems. This increases the ecological value of any area by making it part of a larger whole (Noss, 1983; Harris, 1984). Generally, a long, wide stream corridor with contiguous vegetative cover is the ideal condition. This facilitates the migration of terrestrial fauna and flora species. Invariably, gaps form in the corridor, the frequency and width of which should be designed in response to planned stream corridor functions (FISCRWG, 1998). Gaps affect the filtering ability of the riparian buffer zone by offering no opportunity to slow overland flow or allow for infiltration. Where reference reaches exist, restored areas should be designed to exhibit similar structural diversity and canopy closure to that of the reference reach. The reference stream reach can provide information regarding plant species and their frequency and distribution. Design should aim to maximise the filtering capacity of the stream corridor by minimising gaps in the corridor's width and length (Bren *et al.*, 1997). However, fundamental considerations include whether a particular vegetation type or species has ever existed in the area, and whether the corridor before disturbance was narrow, or part or an expansive floodplain forest system. These factors can play a significant role in the success of a particular rehabilitation project (Knopf *et al.*, 1998). Local conservation objectives should be considered in developing or restoring riparian zones (Veneman, 1994).

(iv) Boundaries

Habitat, conduit, and filter functions are also affected by the structure of the vegetation between the corridor and adjacent landscape (Veneman, 1994). This transition zone is typically straight or curvilinear. A straight boundary minimises species interaction between the two ecosystems (stream corridor and adjacent landscape) by allowing relatively unimpeded movement along the edge. A curvilinear boundary, on the other hand, increases the edge to area ratio and encourages movement between the zones by increasing the edge to edge ratio, resulting in increased interaction. The design of the boundary can be manipulated to enhance the objective intended, thus affecting the conduit, habitat and filter functions.

(v) The importance of diversity

Structural diversity is an important design consideration. The vegetation that makes up the stream corridor, its form, and diversity, can affect function, especially at the site and reach scales. Wind, shading, fauna, and plant growth is affected by stratification. Vegetation occurring at the edge of a corridor is different to vegetation at the interior for a number of reasons. These include, topography, aspect, soil, and hydrology. These are important design considerations. Gradual transition from corridor to adjacent land will soften environmental gradients and minimise disturbances. An abrupt change will be less effective in this regard. Edges that appear abrupt may be restored so that these functions can be maximised. Again, a reference reach will provide the best indication of the criteria required.

Alien vegetation can prevent the establishment of desirable indigenous species or become an unwanted permanent component of stream corridor vegetation, and can prove to be detrimental to corridor condition (Olson & Knopf, 1986). The use of exotic species should therefore ideally be avoided or replaced by indigenous vegetation (for guidelines on exotic plant removal, see below). This attitude is encouraged by many pieces of South African legislation, such as the National Water Act, 1998 (RSA Act number 36 of 1998).

(vi) The influence of hydrology and stream dynamics on corridor rehabilitation

An important consideration regarding the use of reference reaches as a guide for rehabilitation projects is that the original cover and older existing trees might have been established before stream regulation or other changes in the watershed that affect flow or sediment transport characteristics. The implication therefore is that where conditions have permanently changed, the original condition may never be reached. This is an important design consideration and must be born in mind. A good understanding of current and projected streamflow characteristics (such as flooding) is therefore necessary for design and appropriately restored streambanks and plant communities within the floodplain. Water management and planning agencies may be approached, or aerial photography studied, and discussions with local residents may also provide information on water diversions, ground water depletion, and similar changes in the local hydrology.

It is generally advised that projects that require long-term supplementary watering should be avoided due to high maintenance costs and decreased potential for success (Veneman, 1994; Bren *et al.*, 1997; FISCRWG, 1998; Klapproth, 1999). Furthermore, site specific conditions should be considered when choosing species. For example, sites where the soil is saline will require special treatment or species, which can survive high salinity levels. Consideration will also have to be given to the specific requirements of different riparian species. For example, plants that can tolerate extended inundation as adults, may require a draw-down for establishment, and plants thriving on relatively dry sites may be established only on moist surfaces near the water's edge. This may complicate the issue remarkably and may require consideration of how sites may change over time. The implication of simulation models, which predict how plant composition will change, may become necessary. Examples of this kind of more sophisticated plant response model include van der Valk (1981) and Pearlstine *et al.* (1985).

(vi) Exotic plants

In some cases, exotic plants may be beneficial to bank stability, however in others they may exacerbate the problems they were intended to overcome. The important point to note when considering exotic plant removal is weighing up the cost of the revegetation operation in relation to its removal (LWRRDC, 1999b). Other important points, as highlighted by LWRRDC (1999a, b) include the following.

- There may be several metres of head-cuts held up in exotic plant roots in smaller streams. These need to be identified and assessed.
- A widely accepted opinion in that wherever possible, exotic plants should be removed from riparian areas so long that their removal does not trigger large amounts of erosion and their removal will be swiftly followed by their replacement with indigenous species.
- Not all exotics are problematic, in fact, certain species may be out competed by indigenous species once there are established.
- Certain exotic may fulfil a task better than indigenous species and it may therefore be beneficial that they remain. Once the role for which they have been established or allowed to remain has been completed, they may gradually be removed and replaced by indigenous species.

If the decision is made to clear the exotics, they may be removed in one operation provided that:

- They are not performing some vital stabilising role or other role essential to stream continuity. Consider providing alternative stabilising structures before removal

- Other plants should be available to provide shade and other ecological functions on exotic plant removal. If not, indigenous species should be planted and given sufficient time to mature before the exotics are removed.

In addition, the removal of exotic plants should not cause a drastic change in river dynamics. If this is expected, small segments of riparian areas should be cleared at a time so as to minimise the disturbance. It is recommended (LWRRDC, 1999b) that when all exotics are removed in one operation on alluvial banks, equilibrium or aggrading inside bends, or straight reaches:

- Replacement indigenous species are immediately established and maintained
- The roots of the exotic plants are retained to hold the banks until the replacements mature
- Other trees are available to maintain ecological functions
- Structural controls are established before exotics are removed where flow energies are too high for indigenous species to establish

On the other hand, exotics may be phased out on outside bends or straight degrading reaches on alluvial banks provided that:

- They are removed in strips of three along the bank with a resting period of enough time to allow for indigenous species establishment and maturation before commencement of the next phase
- Roots are retained
- Where flow energies are too high for indigenous species establishment, flow structure should be established before removal

Where there is a lack of resources for adequate protection or replacement of exotics, an exotic free zone should not be desired over one that will degrade as a result of a reduced vegetative cover. An exhaustive risk assessment should always be conducted taking into consideration the benefits and potential implications of alien plant removal.

Throughout the text of the literature review, the term *rehabilitation* has been referred to on numerous occasions, while avoiding the use of *restoration*. The purpose of the next section is to clarify what is meant by each term, and to point out their differences within the context of this body of work. The focus will then shift onto the importance of planning, and the benefits that may be gained from a planned rehabilitation exercise.

2.3 Rehabilitation theory

2.3.1 Restoration or rehabilitation

An examination of the literature will show that authors use various terms to describe the process of improving some aspect of riparian ecosystem structure or function, most typically the terms *rehabilitation* or *restoration*. While these terms are sometimes used interchangeably, more often they imply a specific meaning.

(a) Restoration

Jasperse (1998) defines restoration as '*the full structural and functional return of a river to a pre-disturbance state*' or '*the process of returning an ecosystem as closely as possible to pre-disturbance conditions and functions*' (FISCRWG, 1998). NRC (1992) defines it as '*the return of an ecosystem to a close approximation of its condition prior to disturbance*'. Unfortunately it is an opportunity which rarely occurs for the whole of a river. This is even difficult to achieve for discreet sections or reaches of a river, simply because the conditions prior to the disturbance may not be fully known and/or, reference sections may not be available. In addition, each ecosystem is the result of a sequence of events (climatic, biological etc.) which are unlikely to be repeated in precisely the same manner; and the species that once inhabited the area may no longer be available, or if available from other ecosystems, may not be physiologically or genetically identical to the race or sub-species formerly inhabiting the degraded ecosystem (NRC, 1992; Jasperse, 1998). LWRRDC (1999a) defines restoration as '*putting back to good working order*', which is very similar to the definition of rehabilitation (see below). This highlights the danger of using the terms interchangeably, which if done, may cause the loss of the meaning of one of the terms. The emphasis on restoration is that it is an aspiration, and rehabilitation is an achievable goal.

(b) Rehabilitation

In its most simple form, rehabilitation can be considered as a series of actions that make the landscape useful again after a disturbance. Dunster and Dunster (1996) define rehabilitation as '*the recovery of ecosystem functions and processes in a degraded habitat*'. The most important distinction between two terms, as noted by FISCRWG (1998) is that restoration implies a return to a pre-disturbance condition, while rehabilitation refers to an establishment of a geomorphological and hydrological landscape '*that supports the natural ecosystem mosaic*'.

The challenge of rehabilitating rivers and in particular, streambanks, is one which truly shows the importance of emerging sciences such as landscape ecology. It involves at one end of the spectrum the understanding of interrelations between animals, plants, water, and sediment and acquiring knowledge as how to manipulate the process involved. At the other end, it involves a more geomorphological and hydrological perspective, setting the river channel in its floodplain and catchment in order to ensure that manipulations at the local scale are sustainable into the future. Successful riverbank rehabilitation relies on bringing together the skills and determination of specialists from a range of disciplines at all stages of the process, from conception and planning through to implementation and appraisal (de Waal *et al.*, 1995). The co-operation of a range of practitioners enables them not only to achieve high standards within their own sphere of specialisation but also to be appreciative and sensitive to the needs of other parts of the landscape and other specialists who are trying to manage them.

An extremely important part of the rehabilitation effort is the learning process involved with each initiative. Post-project evaluation and documentation, as will be discussed in the next section, are central to the learning process and act as a guide for future workers. The following section has specifically been included in the document to stress the importance of the learning process, and to advise on the planning process to be followed and implemented at the onset of the initiative.

2.3.2 Learning lessons from rehabilitation successes and failures

Despite the increase in rehabilitation initiatives, planning and post-project evaluation has either generally been neglected or not fully implemented (Kondolf and Micheli, 1995). In some cases there has been no post project evaluation, while in others, a lack of advanced planning has resulted in evaluation results being of little use in determining whether or not project objectives have been met. The need for planning post-project evaluation has been illustrated in recent surveys. Holmes (1991) for instance, found that of nearly 100 projects completed on British rivers, only five had documented evaluation, and of 400 aquatic habitat enhancement structures installed in south-western Alberta, USA, only 69% were still structurally stable, and 33% were of low or zero effectiveness in achieving habitat enhancement objectives (O'Niel and Fitch, 1992). Of 161 aquatic enhancement structures in Western Oregon and Washington, USA, 18% failed outright, and 60% were damaged or ineffective (Frissell and Nawa, 1992). Many difficulties may be associated with the lack of evaluation. Amoung these is the difficulty in measuring project success. There is also difficulty in standardising results with regional variation. Often evaluation and associated techniques are not considered until after completion. Furthermore, factors such as the lack of funding and other resources, may come into play compounding the problem. Often finances are for the project implementation only, and further evaluation would not be considered the responsibility of the funding agency.

A systematic approach to post-project evaluation needs to be adopted to avoid making past mistakes. For this to occur, standard guidelines for evaluation need to be implemented in conjunction with the publication of evaluation results. The key to post-evaluation success is the application of standardised, objective measures that can be reproduced despite changes in personnel. A long-term evaluation program may be seen as an equivalent of a management plan for the restored reach (Kondolf and Micheli, 1995). Neglecting to implement the evaluation aspect will lead to forfeiting the investment if the project is permitted to fail. Not all is lost if a project fails however, provided that sound documentation is kept. Inadequate evaluation prevents the next generation of projects from benefiting from the effort.

Thorough and clear documentation during the planning process is therefore required to guide project implementation and to provide a detailed inventory of predicted environmental benefits for agency personnel, the public, and post-project evaluators. Smooth transition during personnel change or during overall plan revision will also be facilitated by sound documentation (Kondolf and Micheli, 1995). A clear plan must be drawn up and documented well in advance of commencement of implementation, and all the stakeholders must be clear of their role before, during, and after implementation. A clear process of planning, implementation and evaluation needs to be drawn up and followed if success and any progress is to be achieved in the rehabilitation world. Figure 14, below, is an example of a typical process used in many rehabilitation initiatives.

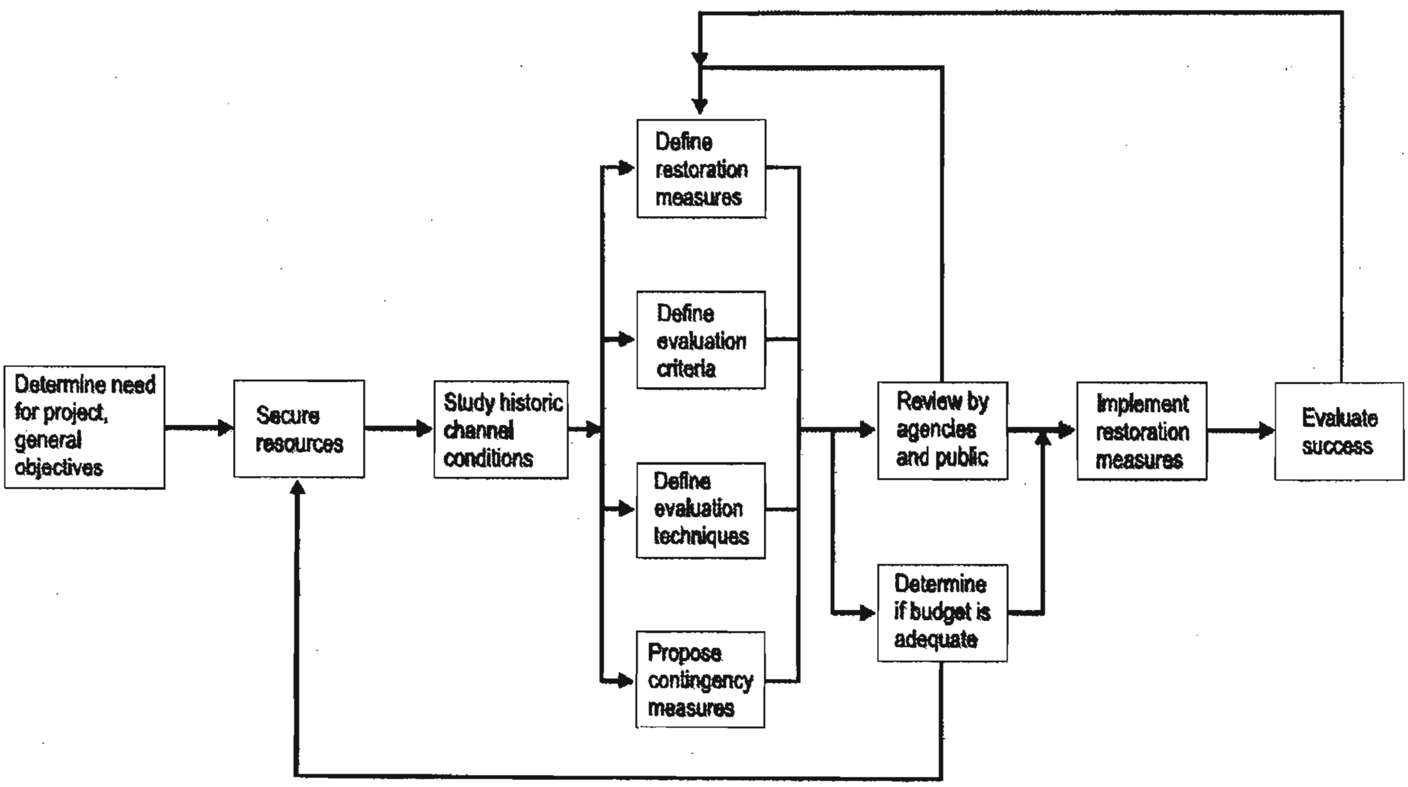


Figure 14: A simplified flow chart of the process of planning, implementing, and evaluating a streambank rehabilitation project (Kondolf and Micheli, 1995).

2.3.3 Planning, implementing and reviewing rehabilitation initiatives

Although rehabilitation initiatives are mostly in response to some unplanned disturbance event, it is almost as often that some *a priori* planning can be made to minimise initial disturbance, thereby reducing the financial and personnel commitments to the post-construction/operation/disturbance rehabilitation initiative. Minimising impacts on buffer zones will reduce influences from increased suspended sediment loads, increase bank stability and protection, and preserve a greater portion of riparian habitat during implementation (Gore *et al.*, 1995). Planning of adequate technique specifications will also ensure increased rehabilitation effectiveness. For instance, adequate buffer strip criteria vary for differing objectives, such as bank stability as opposed to the enhancement of habitat for the breeding purposes of an endangered species.

Planning goes beyond the specifications of rehabilitation implementation however. Aspects before, during, and after implementation, require just as much planning if not more. The planning process is required to guide project implementation from conception and the setting of general objectives, all the way through to project evaluation and documentation, for example Figure 14. The downfall of many rehabilitation initiatives has been the planning process. Often only some of the steps outlined in Figure 14 have been followed, thereby neglecting vital steps for complete success.

(i) Rehabilitation goals and objectives

These need to be firmly in place to guide the overall process. They are also important in affecting the decisions made and the type of techniques implemented. Well-defined objectives should be used to evaluate the success of the scheme (Erskine, 1993).

(ii) Securing resources

Care must be taken early to secure the necessary resources for all components as the project plan is developed and refined. Often project evaluation and follow-up, for example, are not included in initial cost estimates and therefore are often neglected.

(iii) Studying historical channel conditions

Historical data may be an important asset and must be used as much as possible to give an understanding of the area before disturbance. It is also helpful in providing a temporal context in which to interpret evaluation results.

(iv) Defining evaluation criteria and techniques

Defining evaluation criteria and techniques in the project proposal is central to the collection of all relevant data pre-project implementation so that the success of the project may be measured. The need for this to be addressed was illustrated in a project attempting to evaluate a stream rehabilitation venture in Nevada, USA. Although extensive pre-project data had been collected, some goals could not be evaluated because not enough, or inappropriate data had been collected (Kondolf and Micheli, 1995). Such lessons highlight the need to set clear goals and achievable methods of assessing goals before project implementation.

(v) Defining rehabilitation and contingency measures

Project implementers need to be clear about the measures that are taken, which must be in line with the project goals and objectives. It is in this step that rehabilitation techniques are decided upon. It is extremely important to choose techniques for the right job. Many options are available for different outcomes. These must be chosen in accordance with the objectives set in the beginning, and implemented with their design limitations in mind.

(vi) Project review

Once it has been decided what is to be done and how to achieve it, the plan should be presented to the relevant stakeholders. This step will help ensure that nothing has been left out, and whether the project is within its limits. This stage will also bring renewed commitment and support to the project. Should any irregularities be found, provision should be made to correct them at this stage.

(vii) Project implementation and evaluation

It is only at this stage that the project implementation may commence, after which, evaluation of the success will allow the learning phase to begin, as already discussed.

In addition to these steps, there is a need for a system of setting priorities for streambank rehabilitation initiatives. Some authors (Rutherfurd *et al.*, 1999) maintain that pouring resources into rehabilitation initiatives haphazardly may be an expensive approach. Instead, these authors recommend a sequence, from sites most in need of immediate attention (i.e. those that still have ecological value), to those which may be left for the time being (those that require substantial intervention). This approach, it is argued, is a more cost-effective approach to riparian rehabilitation, and streambank rehabilitation in particular. In brief, the authors discourage the setting of unrealistic goals by over-exerting one's capabilities. The message is to set priorities hierarchically, first at the national level, then down to regional, catchment, segment and reach scale. By doing this, the highest impact of a rehabilitation venture will be felt. This aspect of sound rehabilitation will be focussed on in Chapter 3.

CHAPTER 3

Development of a prototype decision support system

3.1 A brief history into decision support

Decision support systems had their origins with the emergence of computer technology in the late 1960's, with which, came the concept of decision support (Quinn *et al.*, 1993); and aimed at using modelling to evaluate alternatives and to arrive at a decision. They were originally designed for use in planning and prediction in industry and commerce (Thieraf, 1982; Bennett, 1983). Large quantities of data were thus becoming easier to analyse. This in turn sparked a similar trend in information technology, where, by the late 1970's, the need for efficient and effective information management systems was well recognised. The objective of Information Management Systems (IMS) was to provide managers with the necessary data to develop management strategies, and the more efficient this process, the greater the advantage for the corporation which developed it. It was soon realised that this was not sufficient and data needed to be analysed and interpreted. Consequently, predictive questions needed to be answered which became the main focus of information management in the 1980's. It became paramount to provide concise and reliable indices of performance to managers. The interface between data sets and managers, usually taking the form of performance indices and predictions, became known as the 'decision support system'(Quinn *et al.*, 1993).

Due to society's increasing complexity and the number and characteristics of the interactions which occur between social, economic, environmental, and political issues, and the non-linear dynamic nature of responses which are difficult to predict, Quinn *et al.* (1993) believe that the adoption of a decision support system is critical for successful environmental management in and beyond the 1990's. The single most important factor for a successful decision support system, as Indignizio (1991) points out, is the creation of a knowledge base. The objective thereafter is to obtain and illustrate, in the knowledge base, the rules employed by a human expert in solving a problem. The process followed by the decision support system involves the user providing it with certain expert information and in return receives expert advice. Internally, this process has two main components: the knowledge base and the inference engine, which draws conclusions (Kotze, 1999).

3.1.1 What is a decision support system?

A decision support system may be defined as a system which exhibits, within specified parameters, an ability in problem solving which is in relation to that of a human expert, by manipulating a knowledge base and a reasoning mechanism (Guida & Tasso, 1989; Indignizio, 1991). Hard data blended with semi-structured procedures and common sense expertise is used with heuristic approaches to problem solving, to allow an appropriate level of detail to be considered for the problem at hand (Negoita, 1985; Scifres, 1987; Stafford Smith & Foran, 1990; Stuth *et al.,* 1990; Stuth *et al.,* 1991; Sheehy *et al.,* 1993). Its ultimate form is a computer system aimed at using modelling to evaluate alternatives and to arrive at decisions. As computer technology developed, the potential for integrating a wider range of information sources followed suit. These include simulation models, expert systems, databases, graphically-oriented systems such as geographic information systems (GIS), remote sensing, remote networks etc. The limitations of these computer based techniques have been recognised however, and as a result, non-computer versions are commonly accepted (Stuth & Stafford Smith, 1993). This may prove particularly important in situations where computers may not be available or appropriate. The term 'decision support system', therefore encompasses systems ranging from tools which assist with a well defined problem area, to those that are open ended in their application, from those that are purely expert systems or simulation models, to those that combine many approaches, from systems requiring computer hardware and personnel trained to use the technology, to those that simulate interactions between managers at a social level (Stuth & Stafford Smith, 1993). All have the common goal of improving decision making, through support, and providing users with a means of assessing alternatives against each other more objectively and comprehensively than could be done previously.

It must be further understood, that information must be organised to be of value, whether at the individual or policy level. Decision support systems help provide a logical framework for this organisation (Stafford Smith & Foran, 1988, 1990; Stuth *et al.,* 1990). They also assist the user in selecting appropriate technologies. Decision support systems in the environmental field are similar to those in other fields in that they are designed for a specific problem area, they incorporate specific planning horizons, and guide decision makers through a process of logical planning and assessment alternatives (Taylor & Taylor, 1987). They are therefore a valuable mechanism in aiding decision makers, or users, to make decisions in their own environments and experiences, to assess the suitability of a technology, and to allow them to impose their own values on the process (Stuth *et al.,* 1991; Ludwig & Sinclair, 1991; Hamilton *et al.,* 1992; Sheehy *et al.,* 1993). A decision support system therefore, has a special capability to aid in problem solving in the field of riparian management.

3.1.2 Making a decision support system managers can use

Although the previous section highlighted the role decision support systems may be able to play in riparian management, the developer of one must not proceed without determining who the users might be, what their problems are, or whether these problems are applicable to a decision support system format.

Probably the most important part of a decision support system, is the focus on the end user. The construction, design, presentation, database contents, and database management procedures should all be designed with the end user's requirements at the fore (Stuth & Stafford Smith, 1993). Consideration of whom the decision makers may be, what their decisions are, and how they make them is required. Caution should be exercised in avoiding the devotion of time and energy on decisions that are not likely to be made. For example, Stuth and Stafford Smith (1993) cite managers in Australia neglecting ecological issues because their primary decision making framework rested on economics. Once environmental issues were explained in terms of economic gains or losses, ecological issues became very much more important. In this case, ecological issues did not need answering, and attempting to support decisions in this way was futile. Another lesson learned from this experience is that the language of the end user should be used for better understanding. Consequently, it should not be assumed that users of the decision support system, automatically identify the different perceptions, priorities, and problems correctly, and target them appropriately.

3.1.3 The decision making process

For a decision to be taken, a certain process has to be followed if the outcome is to be sound. A typical decision making process is to:

- identify that there is a problem
- assess what the problem is impacting upon
- determine the cause of the problem
- propose solutions to the problems
- assess methods of measuring, that clearly detect the degree of success
- document the management decision process and results

It follows therefore, that a human must be present and have the necessary knowledge or wisdom to see that a problem exists, and some form of mitigatory action needs to be implemented. A process is then followed whereby the cause of the problem must be established before solutions can be proposed. Once this has been established, appropriate mitigatory measures may be implemented.

Taking cognisance of the above, streambank rehabilitation cannot be done using a decision support system alone. There are other, complex issues at play. Streambank rehabilitation is an intricate undertaking and is subject to a variety of conditions and characterised by high levels of uncertainty and site specificity. In this light, detailed guidance is achievable only once the dominant forces at play in the system have been identified and are factored into any decision that is taken. For an approach that is inclusive of all issues concerned with sound rehabilitation, the following principles (Kapitzke *et al.*, 1998) will form the backdrop against which the rehabilitation procedure will be shaped.

- Sustainability - provision of long-term ecological functions and utilitarian requirements of streams

- Multiple objectives - adopt multiple objectives that recognise natural stream functions and human uses
- Catchment context - plan rehabilitation work within site and catchment contexts, recognising the different influences and processes that occur at these different scales
- Stakeholder consultation - involves stakeholders in identifying problems, setting objectives, and determining appropriate rehabilitation techniques
- Interdisciplinary approach - integrate hydrological, geomorphological, ecological, and socio-economic considerations in planning and design

These principles are well established in the literature (Brookes & Shields, 1996). They are central to sound rehabilitation and are a solid foundation for progress, although they are not yet fully embraced in South African practice.

3.1.4 The value of decision support systems in streambank rehabilitation

Important characteristics and advantages of decision support systems, in general, as seen by Quinn *et al.* (1993) and Kotze (1999) include the following:

- they provide cost effective solutions to managers. These solutions are based on current understanding and practice
- they play a useful role in the consolidation and evaluation of current understanding
- it is possible to explain their reasoning process in an explicit manner
- the information and inference mechanisms are separate
- they are able to solve problems and dispense advice quickly
- they promote interdisciplinary collaboration and networking

3.1.5 The need for Streambank Rehabilitation Decision Support System (SR-DSS)

Knowledge of rehabilitation techniques is scattered throughout various organisations and literature sources, and a large proportion is not in a form that is easily understandable and applicable to the layperson. Consequently, research papers alone can no longer be regarded as a satisfactory end product of research (Berliner, 1990). Due to the enormity of the task of rehabilitating river banks in South Africa, it is necessary to encourage people such as land owners, managers and other stakeholders to become involved. It is felt that by simplifying the process, more people would be able to implement scientifically sound rehabilitation techniques and principles.

Therefore, there is a need to present this knowledge in a form which is easily accessible and understandable to potential rehabilitators. User-friendly decision support system models, are seen as an efficient means of reaching this end (Quinn *et al.,* 1993). A literature review was conducted in search of the application of decision support systems in general. This revealed that they have been used and applied to a great variety of fields. These include, their application to business problems (Burger, 1995; Burnstein, 1995; Gray, 1996; Klein, 1995; Loudon, 1998), to problems in corporate management (Lofti & Pegels, 1996; Klien, 1990; Turban, 1993), environmental management (Stuth & Lyons, 1993), the advertising industry (Gatignon, 1991), the information technology industry (O' Connor, 1997), to problems in the pharmaceutical industry (van der Van, 1989), and the health industry (Ittmann, 1995). Decision support systems have also been developed for a wide range of natural resource management problems. In South Africa, these include those of Quinn *et al.* (1993) for the development of a methodology for the rehabilitation of riparian zones or streams within sugarcane farming areas; O'Keeffe *et al.* (1987) for classifying rivers according to their conservation status; Starfield *et al.* (1987) for predicting, on a qualitative basis, the effects of salinity fluctuations on the biota of lake St Lucia; and Kotze (1999) for supporting wetland management decisions.

A search was also undertaken for literature specifically designed to help end users in the field of riparian rehabilitation. This revealed that numerous systems had been developed which were specifically designed to help make decisions on issues such as management (Table 1). A factor detracting from their appeal for use in South Africa is that they have been developed mostly for first world countries, primarily the United Kingdom, Australia and the United States of America and focussing on problems specific to those parts. A search for a system which consolidates rehabilitation techniques into a decision support system proved fruitless. In addition, South Africa's, and other developing country's contribution to riparian rehabilitation was found to be limited by comparison. This is thought to be caused by a lack of riparian specialists, funding, and appropriate legislation.

In South Africa, as in many developing countries, the dependence on services performed by riparian areas is generally greater than in developed countries. For this reason, the need for a streambank rehabilitation decision support system is likely to be as great, if not greater in southern Africa and other developing countries than in the United Kingdom, Australia or the United States.

It is stressed though, that the introduction of a streambank rehabilitation decision support system is not intended to replace professional judgement and intensive site-specific investigations where they are required. Instead, it is intended to assist potential riparian rehabilitators in southern Africa to identify a suitable rehabilitation technique for a particular instance by assessing each case individually. The intention is to simplify the task of sifting through the many available techniques so that more energy may be directed to the rehabilitation effort, instead of into repetitive research. Decision support allows for the end user to take an informed approach to river bank rehabilitation in order to isolate probable causes and direct interest to those areas. A systematic approach to objective setting and assessment procedures will enhance the decision making process by allowing classification of the steps and issues involved in determining appropriate solutions to rehabilitation issues. The tool allows for key priorities, as determined by the relevant user, to be examined in comparison with other priorities and rehabilitation activities at a catchment, reach or site scale, to maximise benefits. Multiple benefits or constraints of priorities and/or activities can therefore be drawn out, increasing cost effectiveness.

3.2 Field assessment sheet and SR-DSS

The idea behind SR-DSS, as with any other decision support system, is to provide expert advice to the user. Many techniques for streambank stabilisation have been developed over time (FISCRWG, 1998; Vivash & Murphy, 1999) and their variety of uses may seem overwhelming and confusing to potential users. These techniques are scattered in the scientific literature and may pose a problem to access by the average person intending to restore or rehabilitate channel banks. The idea of a decision support system specifically geared towards the selection of streambank rehabilitation techniques is therefore unique and serves to assemble all available methods in the literature and empower the riparian manager to use them. SR-DSS works in two phases, which are completed at the site. The sites are put into an order using a priority setting model (discussed below). The first phase of SR-DSS, the user is referred to a field assessment sheet, following which, the flow chart (phase 2) is used. These will be discussed in more detail below.

(i) Phase 1: The field assessment sheet

Phase one begins with the introduction of a field assessment sheet (see Table 3) which the user is required to complete at the site which has been chosen through the priority setting model. The assessment sheet attempts to evaluate the severity of the degradation that has taken place and so indicate the level of intervention required. This is done through a system of scores which are given to various forms of bank condition, eg. a bank of less than 1.5 metres in height is given the lowest score due to the likelihood that a smaller bank will be less vulnerable than a bank of greater than 2.5 metres. The same goes for the steepness of the bank where a bank of less than 10° will be less vulnerable than a bank of greater than 81°. Eight criteria are represented on the field assessment sheet. These include a section on bank materials, location of the site relative to other stream features eg. inside meander, present status of the bank ie. actively eroding, dormant etc., severity of degradation, geotechnical failures, and the state of the vegetation. The scores range from 1 to 5, and are tallied on completion of the assessment to give a final score. It must be noted that the field assessment scores are separate from the priority scores, which are obtained from a table specially developed for that purpose. This will be discussed below. The field assessment scores

3.3 A framework for streambank rehabilitation

Much of the literature on riparian rehabilitation, promotes an integrated, system-based approach to natural resource management (State of the Environment Advisory Council, 1996; Petersen *et al.,* 1992; Kapitzke, 1999; Lucas *et al.,* 1999; Erskine & Webb, 1999; Walsh & Breen, 1999; Heron *et al.,* 1999). This approach requires a management planning framework operating at a range of spatial scales that considers all aspects of resource use, and provides for local action to address specific issues such as bank stabilisation and habitat rehabilitation within the broader catchment and regional contexts. Although SR-DSS attends to local site specific problems, it must be used in a holistic frame of mind towards the catchment. In this regard, the adoption of the river catchment as a basic unit for natural resource management, will help recognise spatial characteristics and stream processes, consider social, economic, environmental and other issues, develop links between problems and causes, and can help establish land use control and rehabilitation programs within the catchment. It is within this framework that SR-DSS should be used. It should be extended and applied to the whole catchment, while avoiding its application at a specific site (of course SR-DSS may be used on its own to seek advice on a site that has already been chosen by the user) without the consideration of the consequences of the action that is taken. For example, Lucas *et al.* (1999) cite water impounds behind a weir (which was constructed without full consideration of the ecological consequences), decreasing the river gradient while increasing erosion downstream leading to changes and losses of habitat and bank stability in the Murray-Darling Basing, Australia.

A broad context within which the rehabilitation process may be applied is provided by Kapitzke (1999). This is a four tiered process, intended to protect the environment and achieve ecological sustainability:

- represented at the highest planning level is the integration of environmental protection measures with planning and resource management functions incorporated into a hierarchical management framework with the regional waterway and urban storm water management strategies
- the next level contains local strategies and actions to manage a wide range of local catchment issues, and catchment management plans are linked to outcomes for the whole region
- the third level involves planning at the reach level relating to flooding, stream condition, water quality or ecological health priorities
- the fourth level in the management framework is the local management plan which usually details specific issues such as local waterway actions in the form of revegetation or streambank stabilisation

Although a broad management framework (above) has been recognised as important to stream management, stream managers still require more than this to meet bank rehabilitation objectives. A need has also been recognised by Kapitzke (1999) to overcome the deficiencies that relate, to poor project objective definition, incorrect diagnosis of problems and causes, a lack of catchment context for analysis and rehabilitation options that do not take into account natural stream function. There is a need therefore, to extend the above framework to meet these deficiencies. Kapitzke (1999), provides just such an extension, with what he calls the Conceptual Framework. This conceptual framework has the following as its basis:

- the recognition of human stream uses and natural stream values
- the recognition of anthropogenic pressures on the stream system
- the facilitation of an understanding of stream processes
- the identification of the relationships between problems and causes, and,
- the suggestion of rehabilitation options, which meet the desired user objective

The Kapitzke (1999) conceptual framework, can thus form the basis of the planning, design and implementation phases of a rehabilitation scheme which has already been shown to be successful by Kapitzke *et al.* (1998). It identifies human use of a stream and recognises the pressures that may be exerted following these uses. It further recognises that problems arise as a result of conflict between human use, pressures on the stream and natural stream processes. Problems therefore arise when stream processes impact on human uses, human pressures, or the effects of accelerated human pressures, impact on stream processes. Therefore, the objectives to deal with these problems must relate to the problem itself, to the associated human pressures, and the human use, and not the symptom (Kapitzke, 1999). Strategies or objectives, offering solutions to the symptom of a problem will only create a temporary solution, which will wear off as the problem gets worse. This, in effect, will create more damage, and make the problem more difficult to fix.

Using Kapitzke's (1999) conceptual framework for stream rehabilitation, responses to stream management problems in general should be based upon:

- an understanding of the nature and cause of the stream problem(s)
- an understanding of stream processes
- an awareness of the present, and future human use of the stream
- an understanding of the human pressures affecting the stream
- a range of objectives that reflect the different needs and expectations of the various users of streams and their environments

The final product of this conceptual framework is an eleven-step process adapted from Kapitzke (1999), which embraces all the above principles. This model will be discussed in section 3.5, after the discussion on the priority setting model (section 3.4) because it embraces the entire rehabilitation procedure into a logical process.

Another important step in the rehabilitation project is to choose the most appropriate sites within a catchment or region to begin rehabilitation work on. In order to select the most appropriate sites, a selection method needs to be developed whereby the sites are compared to one another to determine which needs immediate attention and which may be left for the time being.

3.4 A method for setting priorities for environmental aspects of stream management

Whereas money being spent on severely degraded stream reaches may make the most sense and a good place to start, it is not always the best way to allocate resources if the goal is ecological rehabilitation (Rutherfurd *et al.*, 1999). It is argued, by the said authors, that it would be more efficient to save entire reaches, rather than to attempt to rescue individual species or communities and leave the reaches to be destroyed. Rutherfurd *et al.* (1999), are of the opinion that the following priorities should be followed when riparian rehabilitation is undertaken:

- ecologically valuable reaches should be saved before less valuable reaches are saved
- streambanks that are in the best general condition should be conserved, before trying to improve on the ones that are in poor condition
- streambanks should be stopped from deteriorating instead of waiting for them to stabilise and then trying to accelerate recovery
- reaches that are easy to fix should be improved on first, and reaches that are extremely damaged should be improved on afterwards
- important structures such as bridges and property should always receive immediate attention

It is on the basis of these priorities that the priority setting model developed in this document will be based.

Following this, how is the decision made which site, reach, or catchment deserves immediate attention, and which could be left for the time being. For this purpose, Heron *et al.* (1999), developed a method to assist in setting priorities between competing projects. It has been dubbed "The Environmental Risk Assessment and Priority Setting Model" or "ERAPSM" by its authors, and was developed in response to the need to determine priority waterway management activities in an environment of competing projects and limited resources. It is a data management system that provides a tool for ranking program priorities on the basis of environmental risk. Heron *et al.* (1999), describe environmental risk as a function of the severity or threats to a waterway and the subsequent values or merits, where the greater the risk, the greater the potential loss of values due to threatening processes. However, for the purposes of this document, and in alignment with Rutherfurd *et al.* (1999), ERAPSM has been modified such that the priority in protecting or enhancing stream processes is given to areas of lowest score, where the consequence of losing such values, which are presently functioning, is greatest.

3.4.1 Risk analysis adapted from Heron *et al.'s* (1999) priority setting method

Rules are applied to each of the values and threats to determine a threat and value rating score for a streambank (Tables 4 and 5). The risk scores are calculated by using the following formula:

Total Priority Score = (sum of all values) x (sum of all threats)

Max score = (5x3)x(6x5) = 450

It follows that the lower the score, the higher the priority of that site or reach. In addition to this set of scores or priority indices, the following rules take precedence over site scores (adapted from Rutherfurd *et al.* (1999)):

Table 2: Presents the rules which are an exception over the site scores.

- First priority is given where the integrity of important structures is threatened, such as property, buildings, bridges or fords.
- Second priority to sites, other than important structures, that are easy to fix or have value that may be lost if left to deteriorate (usually sites with better priority scores)
- Third priority to badly degraded sites which will be difficult to fix or require a large amount of resources (usually sites with poor site scores)

Firstly, group the sites into the three broad categories above. Secondly, within these three priority levels, apply the scores (where the lower the score the higher the priority). Where sites yield similar priority scores, or are in similar condition within these three priority levels (eg. within 30 points of each other) the following rules may be used to give priority to sites:

- Rare sites, or sites in better condition are to be conserved first
- Work down from the source
- Rank according to trajectory (deteriorating before improving), and ease of job (easy to fix before difficult)

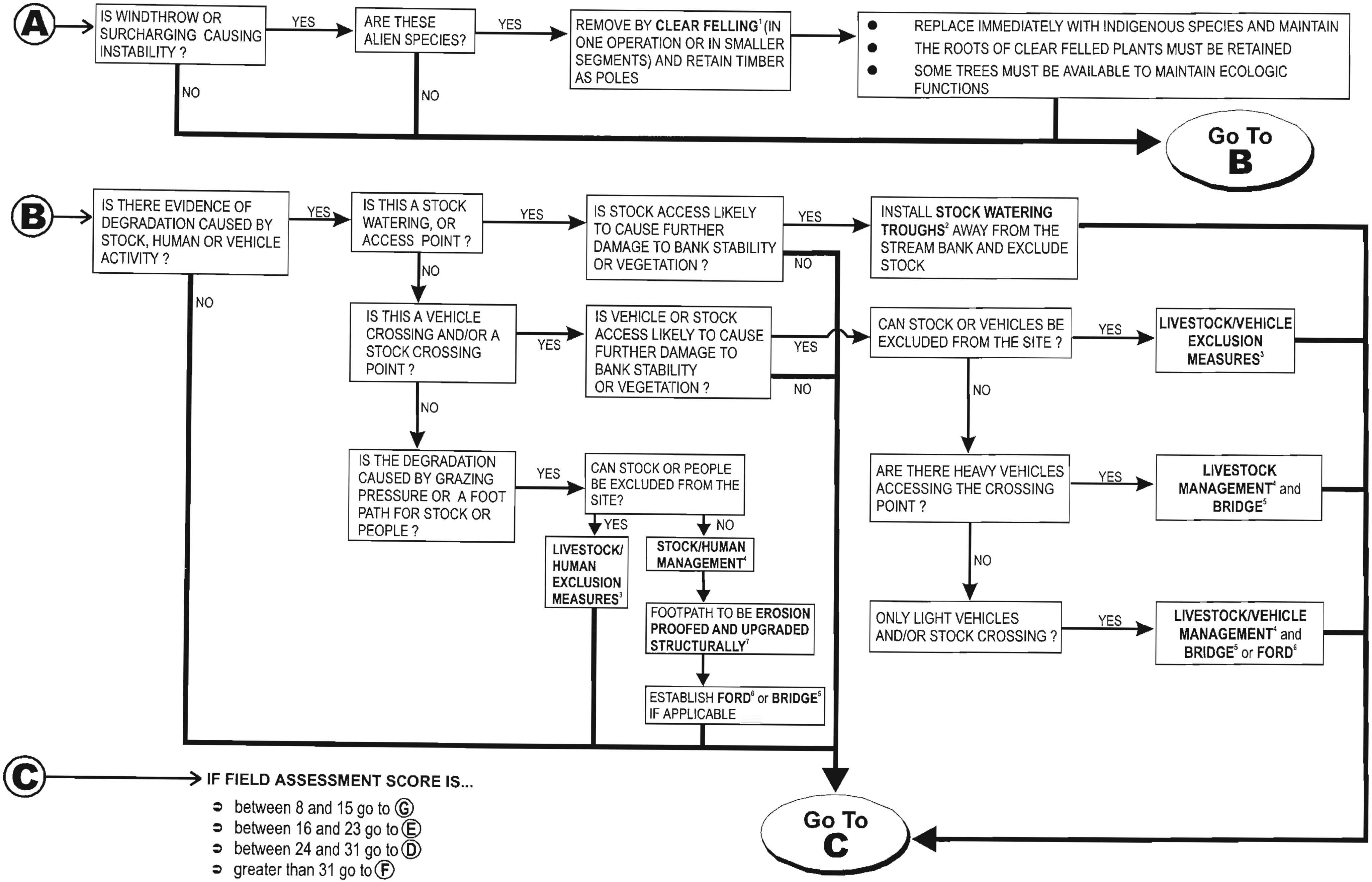
Table 3: Field assessment of bank stability

CRITERION	SCORE				
		2	3	4	5
Bank height	< 1m	1m to 1.5m	1.5m to 2m	2m to 2.5m	2.5m to 3m
Bank steepness	< 10° flat	10 to 30° low	31 to 60° moderate	61 to 80° steep	> 81° very steep
Bank materials: uniform	boulders or bedrock	cobbles or boulders	silt or clay	gravel or sand	sand
Bank materials: layered	boulders, bedrock and layered cohesive materials	predominantly cohesive materials but with some uncohesive	approximately equal proportions of cohesive and uncohesive materials	predominantly uncohesive sediments but with some cohesive layers	predominantly uncohesive sediments with few cohesive layers
Location	inside meander or depositional environment	parallel flow or impinging flow or low energy environment	seepage/runoff points or behind bar or impinging flow or parallel flow in high energy or wave action	flood plain scours or opposite bars or relatively high energy environment	outside meander or near a structure or reach wide
Status	stable and evidence of sediment accumulation	stable	unstable but dormant	unstable active or uncertain	unstable active or eroding or toe scour
Severity of degradation	insignificant	mild	moderate	serious	very serious
Geotech failures and erosion	no geotech and little erosion [illegible] perhaps mild sheet erosion	no geotech failures, perhaps sheet erosion or minor rilling	no geotech failures, major sheet erosion, major rilling or minor gullying	tension cracks < ½ bank height, geotech failures (shallow slides, soil or rock fall, piping) or moderate gully erosion	tension cracks ≥ ½ bank height, rotational slip, slab, cantilever, pop-out, or serious gullying
Vegetation	High root density, trees, shrubs and grass with buffer [illegible] 100% canopy cover	Moderately high root density, canopy cover 60 to 79%, width 5m or more	Moderate root density, at least 41 to 59% canopy cover, width 5 m or more	low root density few deep rooted, little shallow rooted, canopy cover 40 to 20%	no deep rooted veg, little shallow rooted, canopy cover < 10%

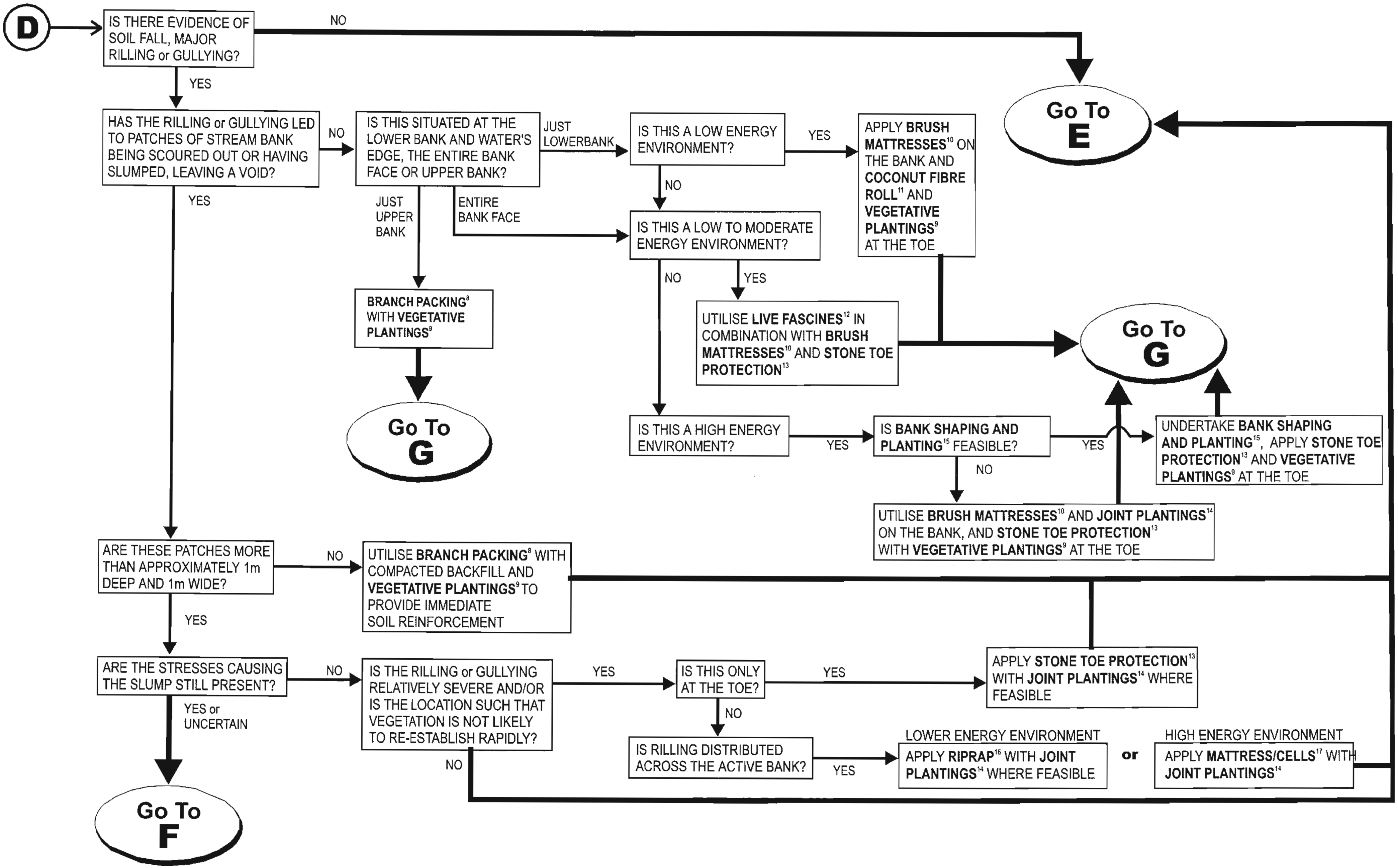
Max. score: 40

Min. score: 8

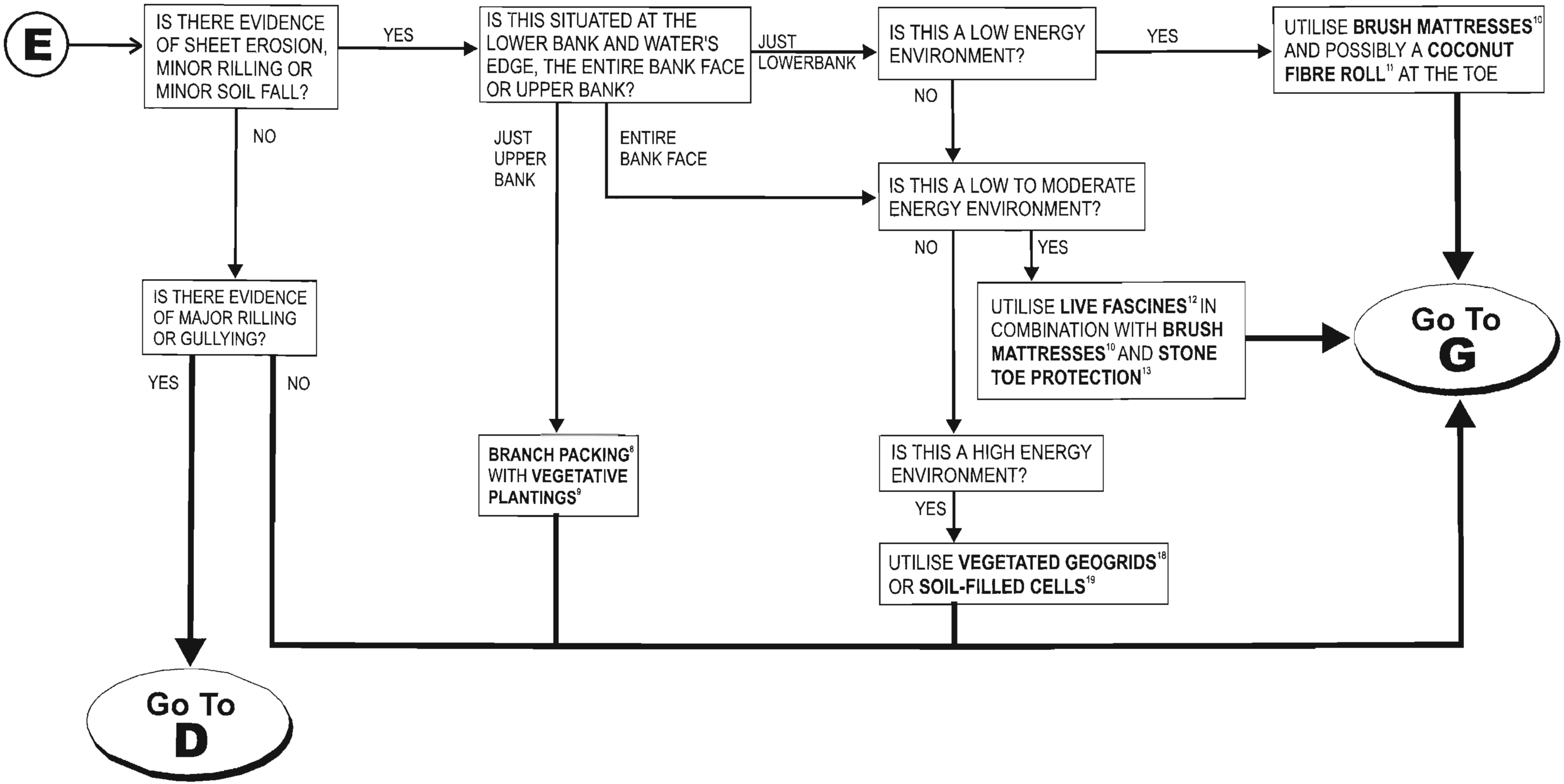
Figure 15: Flow chart presenting Streambank Rehabilitation Decision Support System.



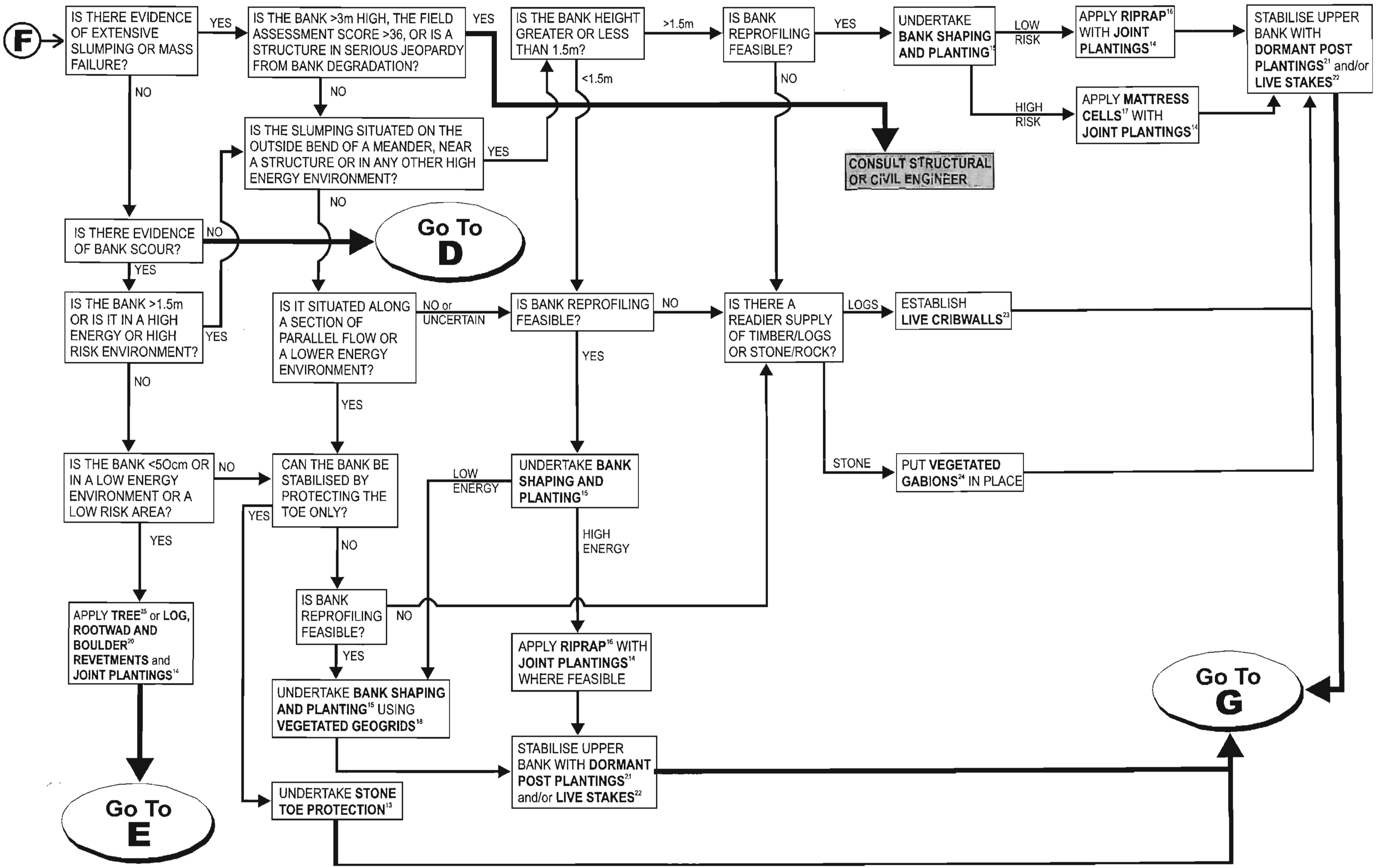
Subscripts refer to techniques in Appendix 2.



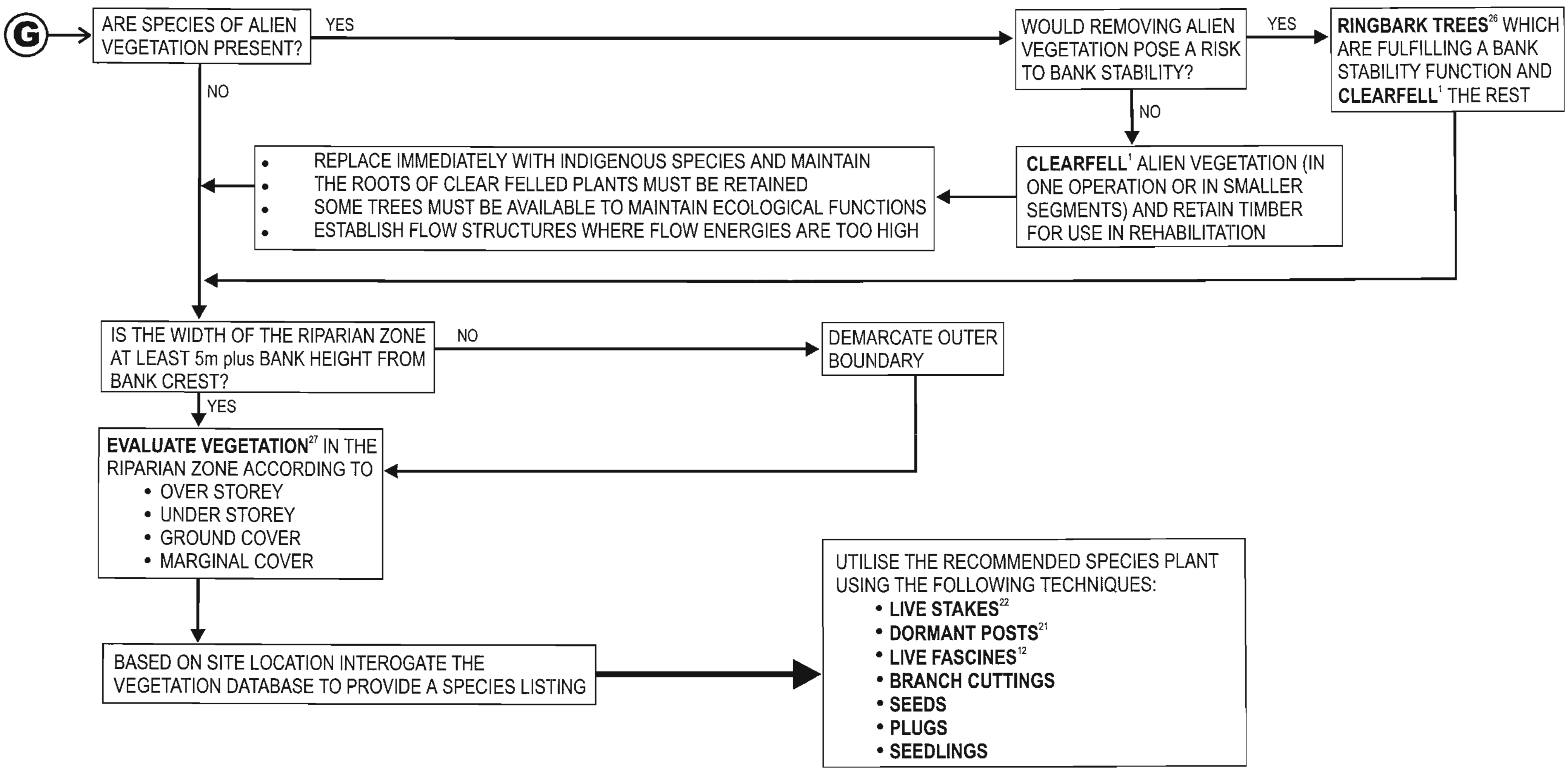
Subscripts refer to techniques in Appendix 2.



Subscripts refer to techniques in Appendix 2.



Subscripts refer to techniques in Appendix 2.



Subscripts refer to techniques in Appendix 2.

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Table 4: Rules for determining value rating (adapted from Heron *et al.,* 1999)

Rating	Very high value	High value	Moderate value	Low value	Very low value
Value Score	1	2	3	4	5
Threatened, rare, or significant species	> 3 present	1 - 3 present	0		
Bank Vegetation	A contiguous stand of mature riparian forest established at least the recommended minimum width for its location (ie. 5m plus the height of the bank). No alien species present.	Slightly modified, indigenous species composition present along both banks possibly with some grassed areas.	Significant presence of under storey exotics mixed with remnant indigenous species. Indigenous over storey generally remaining with some cleared grassed areas, or one side cleared with other virtually undisturbed.	Remnants of indigenous under storey. Under storey dominated by exotics. Ground cover mainly consists of introduced exotics.	Lacks one or more structural elements (Over storey, under storey, ground cover, or marginal cover), is in a generally degraded condition, is less than the recommended width for its location and performs no stabilising role. Consists mainly of introduced species.
Verge vegetation	A contiguous stand of mature riparian forest established at least the recommended minimum width for its location (ie. 5m plus the height of the bank). No alien species present.	Mainly undisturbed indigenous vegetation, or some exotics or reduced cover. Minor areas of disturbance with possibly some small areas of introduced grasses.	Wide corridor of mixed indigenous and exotic species, with the one side cleared and the other reasonably undisturbed and > 5m plus the height of the bank wide.	Narrow corridor of indigenous or exotic vegetation (< 5m plus the height of the bank wide).	Both sides cleared with introduced ground cover.

Table 5: Rules for determining threat rating (adapted from Heron *et al.*, 1999)

Rating	Very low threat	L ow threat	Moderate threat	High threat	Very high threat
Threat Score	1	2	3	4	5
Bank Stability	Excellent	Good	Moderate	Poor	Very poor
Bank vegetation	A contiguous stand of mature riparian forest established at least the recommended minimum width for its location (ie. 5m plus the height of the bank). No alien species present	Slightly modified, indigenous species present along both banks possibly with some grassed areas	Significant presence of under storey exotics mixed with remnant indigenous species. Indigenous over storey generally remaining with some cleared grassed areas, or one side cleared with other virtually undisturbed.	Remnants of indigenous under storey. Under storey dominated by exotics. Ground cover mainly consists of introduced exotics	Lacks one or more structural elements (Over storey, under storey, ground cover, or marginal cover), is in a generally degraded condition, is less than the recommended width for its location and performs no stabilising role. Consists mainly of introduced species
Verge Vegetation	A contiguous stand of mature riparian forest established at least the recommended minimum width for its location (ie. 5m plus the height of the bank). No alien species present	Mainly undisturbed indigenous vegetation, or some exotics or reduced cover. Minor areas of disturbance with possibly some small areas of introduced grasses	Wide corridor of mixed indigenous and exotic species, with the one side cleared and the other reasonably undisturbed and > 5m plus the height of the bank wide	Narrow corridor of indigenous or exotic vegetation (< 5m plus the height of the bank wide)	Both sides cleared with introduced groundcover
Naturalness of channel	Natural	Natural with some modification (minor de-snagging or straightening)	Natural with extensive modification (major de-snagging, straightening, channel enlargement)	Constructed, un-lined	Constructed, lined
Barriers	1	2 - 5	6 - 9	10 - 15	> 16
Exotic Species	Zero infiltration	Few isolated patches on banks and verges (< 10% presence)	More frequent patches (10 - 40% presence)	Significant presence on banks and verges (40 - 80%)	Most of corridor infiltrated (> 80%)

3.5 A model for an holistic rehabilitation procedure

A model which encases Kapitzke's (1999) conceptual framework; Heron *et al.*'s (1999) priority setting model, and SR-DSS, is a structured planning and design procedure, chosen and adapted from Kapitzke (1999). This procedure is a streambank rehabilitation approach which follows a straightforward, yet rigorous process that addresses a broad range of issues and leads from priority setting, to problem definition, through to the choice of objectives, to determination of the strategy or treatment outcome. It is believed that the final product, or rehabilitation procedure, is an holistic and thorough approach to streambank rehabilitation. This approach is an eleven-step process (Table 6) which provides a consistent strategy to address stream management issues at a regional scale, down to the design of suitable rehabilitation strategies for a specific site. It can be grouped into six sequential phases, leading from priority setting, to concept, to feasibility and implementation, to monitoring and review. The eleven step procedure guides managers through the project phases. Heron *et al.*'s (1999) priority setting model selects the most appropriate site to start the rehabilitation operation. SR-DSS assists in the choice of rehabilitation strategy at the specific site. While the planning and design model of Kapitzke (1999) links the broader catchment and reach issues, Heron *et al.*'s (1999) model, and SR-DSS into an holistic framework. It is believed that SR-DSS assists the user in steps 6, 8 and 9 of Table 6. The user of Kapitzke *et al.* (1999) planning and design procedure may leave the manager stranded and confused, leaving no options open to him/her. SR-DSS on its own, on the other hand, is too site specific and does not address the entire catchment and its issues. Vital questions are therefore neglected, such as where to prioritise or where to begin rehabilitation work on any particular catchment. The phased approach to the procedure provides information at the most relevant time in the project allowing, for example, important issues to be considered in a broad sense at a regional management level, and minimising effort extended to these projects which do not proceed to implementation. Furthermore, distinction between phases will be less well defined for smaller projects. For example, where solutions are obvious, the feasibility phase may not be required. Nevertheless, it is recommended that the sequential phases be followed in order to meet the broad objectives of suitable stream management.

Table 6: Planning and Design Procedure [adapted from Kapitzke (1999)]

Phases	Steps	Description
Priority setting	Step 1	Identify the most suitable sites to begin rehabilitating
Concept	Step 2	Identify and describe the problems or issues
	Step 3	Identify the relevant uses and pressures
	Step 4	Examine the stream processes and determine the causes
	Step 5	Define the rehabilitation objectives and constraints
	Step 6	Identify the rehabilitation options and concept designs

Feasibility	Step 7	Feasibility designs and evaluation
	Step 8	Decide on the rehabilitation program
Implementation	Step 9	Detailed design and implementation
Monitoring and maintenance	Step 10	Monitor and maintain
Review	Step 11	Review project

An example has been adapted from Kapitzke (1999), which illustrates the use of the priority setting model, the conceptual framework, the planning and design procedure and the use of SR-DSS for a streambank rehabilitation project. This may be seen in Appendix 2.

CHAPTER 4

A case study on the Foxhill Spruit

4.1 Testing SR-DSS

To test SR-DSS, the Foxhill Spruit in Pietermaritzburg, South Africa was selected. The study area is shown in Figure 16, which is a 1: 3000 orthophoto of the Foxhill Spruit catchment. Due to its size, the Spruit enabled the system to be tested on a catchment basis, which allowed the priority setting model to be tested at the same time. This was done by walking down the catchment from the source, and at every site which was judged with the naked eye to be degraded a priority score was given, using the priority setting model. One's discretion is used at this point to differentiate between a bank requiring human intervention and that not requiring intervention. Signs indicating that human intervention is required may be eroding or collapsing banks. Using the field assessment sheet produced a field assessment score, while a rehabilitation technique was selected by the decision support system. A photograph of each site was taken for further analysis should that have been needed. These are presented in the document. The choice of technique of the decision support system was compared with what a specialist at the site would have chosen in order to determine if sound advice was in fact given. This made it possible to detect irregularities and errors within SR-DSS and allowed them to be corrected. Furthermore, the field assessment sheet was calibrated to determine if the user was guided to the appropriate section on the decision support system. The physical testing of the system proved to be an invaluable experience as it presented real problems for which solutions from SR-DSS were generated. It was only in the testing process that SR-DSS could be smoothed out and depended on to yield workable solutions.

4.2 The rehabilitation approach

It is observed from chapter three, that a process should be followed for a holistic rehabilitation procedure. Form Table 6 in Chapter 3 we are required to fulfill a number of steps:

Step 1

Identify the most suitable sites to begin rehabilitating

In this step, the sites are scored using the table adapted from Heron *et al.* (1999). The priority scores derived for each site are as follows (for convenience, the field assessment sheet scores are also given):

Site no.	PS*1		Individual scores*3	FAS*2		Individual scores*3
1	60	→	(2+2+2)x(1+2+2+2+1+2)	11	→	(2+2+1+2+1+1+1+1)
2	150	→	(3+4+3)x(1+3+4+2+1+4)	13	→	(4+3+1+1+1+1+1+1)
3	300	→	(5+5+5)x(1+5+5+5+2+2)	22	→	(5+5+1+3+2+1+1+4)
4	345	→	(5+5+5)x(4+5+5+4+3+2)	35	→	(5+5+2+5+5+4+4+5)
5	308	→	(5+5+4)x(3+5+4+3+3+4)	24	→	(5+5+2+4+2+1+1+4)

Site no.	PS*[1]	Individual scores*[3]	FAS*[2]	Individual scores*[3]	(continued)
6	312 →	(4+4+5)x(4+5+5+3+3+4)	35 →	(5+5+2+5+5+5+4+4)	
7	375 →	(5+5+5)x(5+5+5+4+3+3)	32 →	(5+5+2+2+5+4+4+5)	
8	336 →	(5+4+5)x(4+4+5+4+3+4)	31 →	(4+5+2+5+4+3+4+4)	
9	220 →	(3+4+4)x(3+4+4+3+3+3)	23 →	(5+5+2+2+3+2+2+2)	
10	200 →	(3+4+3)x(4+4+3+3+3+3)	28 →	(5+5+2+2+4+4+4+2)	
11	220 →	(3+3+4)x(5+3+4+3+3+4)	31 →	(4+5+1+5+5+5+4+2)	
12	325 →	(3+5+5)x(4+5+5+4+3+4)	33 →	(4+5+2+5+5+5+4+3)	
13	242 →	(3+4+4)x(5+4+4+3+3+3)	36 →	(4+5+2+5+5+5+5+5)	
14	264 →	(3+4+4)x(5+4+4+4+3+4)	34 →	(5+5+1+5+5+5+5+3)	
15	153 →	(3+3+3)x(3+3+3+3+3+2)	24 →	(4+5+1+4+2+4+2+2)	
16	144 →	(3+3+3)x(3+3+3+2+2+3)	20 →	(4+4+1+2+2+2+2+3)	
17	190 →	(3+3+4)x(2+3+4+4+3+3)	20 →	(4+4+3+2+1+2+1+3)	
18	325 →	(3+5+5)x(4+5+5+4+3+4)	31 →	(4+5+2+5+4+4+4+3)	

*[1] Priority Score

*[2] Field Assessment Score

*[3] Individual scores that compute the final score (In order from top to bottom of Tables 4,5 & 3).

From these scores it is possible to obtain a list of sites from highest priority to lowest, remembering that the lower the score, the higher the priority. The exceptions to the priority scores must also be taken into account, remembering that:

- **First priority is given where the integrity of important structures is threatened, such as property, buildings, bridges or fords.**
- **Second priority to sites, other than important structures, that are easy to fix or have value that may be lost if left to deteriorate (usually sites with better priority scores)**
- **Third priority to badly degraded sites which will be difficult to fix or require a large amount of resources (usually sites with poor site scores)**

Firstly, group the sites into the three broad categories above. Secondly, within these three priority levels or groups, apply the scores (where the lower the score the higher the priority). Where sites yield similar priority scores, or are in similar condition within these three priority levels (within 30 points of each other), the following rules should be used to rank the sites:

- **Rare sites, or sites in better condition are to be conserved first**
- **Work down from the source**
- **Rank according to trajectory (deteriorating before improving), and ease of job (easier to fix before difficult)**

Therefore, sites must be divided into their three priority classes:

Priority group 1: Sites 4, 8, 10, 11, 12, 14, 17, 18 - due to their proximity to structures and buildings and the potential for damage to occur to structures at those sites.

Priority group 2: Sites 1, 2, 9, 15, 16 - sites other than important structures, that are easier to fix or have value that may be lost if left to deteriorate (sites with better priority scores).

Priority group 3: Sites 3, 5, 6, 7, 13 - badly degraded sites which will be difficult to fix or require a large amount of resources (sites with poor site scores).

Within these priority groups, the sites that are within 30 points of each other are subjected to the remaining three rules, and those that are more than 30 points of each other, the lower priority score takes preference.

Therefore, the order of priority has been calculated as follows:

Priority		**Site no.**	**Priority**		**Site no.**	**Priority**		**Site no.**
1	-	**11***	7	-	**12***	13	-	**9****
2	-	**17***	8	-	**18***	14	-	**13*****
3	-	**10***	9	-	**1****	15	-	**3*****
4	-	**14***	10	-	**2****	16	-	**5*****
5	-	**4***	11	-	**15****	17	-	**6*****
6	-	**8***	12	-	**16****	18	-	**7*****

* - Priority group 1

** - Priority group 2

*** - Priority group 3

SITE 11

Step 2

Identify and describe the problems or issues

Although this site seems to have enough vegetation protecting it, its position on an outer meander makes it a high energy environment. The bank is 2 to 2.5 metres high and > 81°. There is a presence of alien vegetation. There is private property on the bank crest which may be undermined in the near future should no structural support be given. Complicating the issue and creating a higher energy environment is a culvert above the site. This culvert serves as an exit for rain water from Rudling Road.

Step 3

Identify relevant uses and pressures

Bank crest is used as residential property. Pressures on the site include urban encroachment culvert construction upstream of the site, alien species invasion, and the high energy environment.

Step 4

Examine the stream processes and determine the causes

Water flowing down the stream, is directed against the site as a result of its position on an outer bank. The culvert upstream increases the velocity of the water, and the presence of human inhabitants on the crest further deceases the stability of the bank.

Step 5

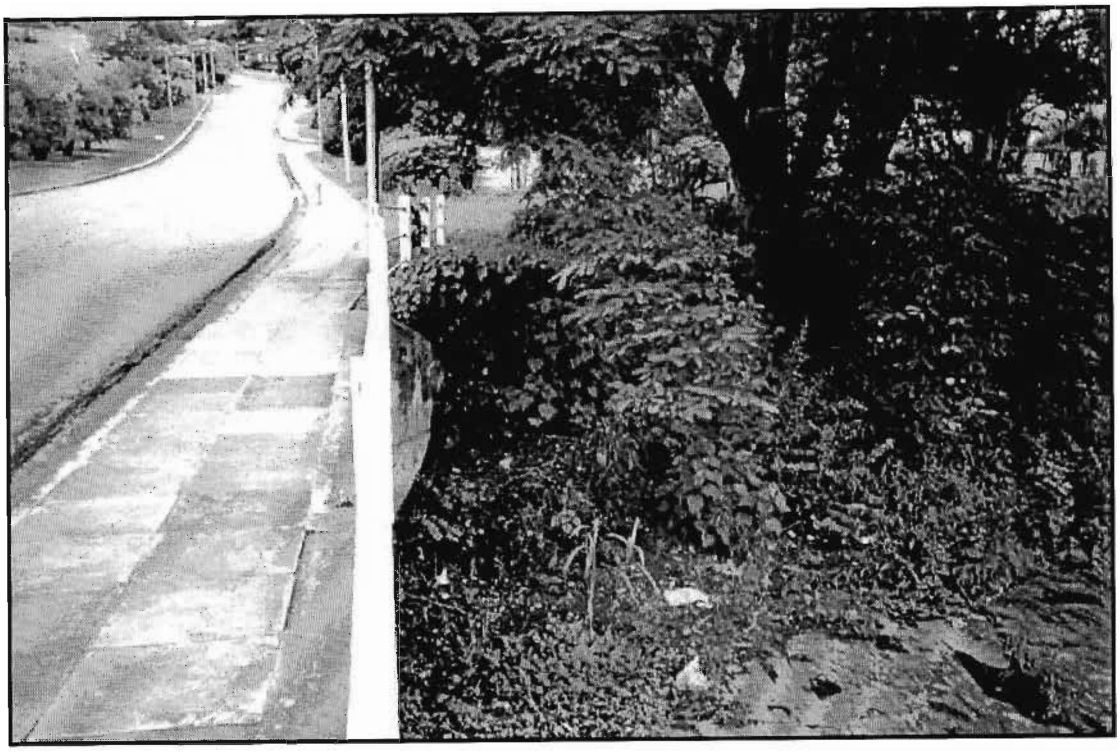
Define the rehabilitation objectives and constraints

Objectives include stabilising and supporting the bank so that slumping and scouring processes are arrested. Directing the force of the water against something other than the bank (ie. using an obstruction to minimise the force), clearing alien vegetation and establishing a healthy riparian vegetation structure of suitable zone width. These activities are constrained by the availability of resources and land for the extension of the riparian zone width.

Step 6

Identify the rehabilitation options and concept designs

Establish live cribwalls or vegetated gabions depending on supply; Stabilise upper bank with dormant post plantings or live stakes; Clearfell exotic species; Demarcate outer boundary of at least 7.5 metres from bank crest (5m + height of bank). Evaluate vegetation in the riparian zone according to over storey, under storey, ground cover and marginal cover; Derive species list from vegetation database (Table 7 and Kellner *et al.*, 2000); Plant the recommended species to the zone width.



SITE 17

Step 2

Identify and describe the problems or issues

Although not a problem yet, this site serves as an access point for humans who seek shelter under Lindup Road Bridge. The ground is therefore bare and may slowly be eroded by sheet erosion over time, eventually undermining the bridge. No severe degrading processes act on the bank as yet. There is a presence of alien vegetation at and near the site.

Step 3

Identify relevant uses and pressures

The site is used as an access path to the bridge. Pressures include, alien species invasion, and human trampling of the vegetation.

Step 4

Examine the stream processes and determine the causes

Human activity on the bank has forced the vegetation on the site to die back.

Step 5

Define the rehabilitation objectives and constraints

Objectives include, either stopping humans from accessing the site or providing alternative access points, establishing a suitable vegetation structure and zone width and clearing alien vegetation. Objectives may be constrained by a lack of resources and the willingness of humans not to access the site or to use alternative access points.

Step 6

Identify the rehabilitation options and concept designs

Human access should be managed, and the footpath erosion proofed and upgraded structurally (e.g. steps leading under the bridge); Ringbark alien trees which are fulfilling a bank stability function and remove the rest on both banks; Demarcate outer boundary of at least 7.5 metres (5m + height of bank). Evaluate vegetation in the riparian zone according to over storey, under storey, ground cover and marginal cover; Derive species list from vegetation database (Table 7 and Kellner *et al.*, 2000); Plant the recommended species to the zone width.

SITE 10

Step 2

Identify and describe the problems or issues

Banks are 2.5 to 3 metres high and >81°. Vegetation lacks an under storey and comprehensive over storey, the riparian zone is narrow, alien species are also present. Bank instability threatens private property 5 metres from the bank crest.

Step 3

Identify relevant uses and pressures

The site is being used as a dumping ground for garden refuse, and as an orchard. The bank crest and verge vegetation is consistently cut back so that no over and under storey vegetation may take root. Pressures include alien species invasion and the habitual removal of vegetation.

Step 4

Examine the stream processes and determine the causes

The dominant process is slumping and mass soil fall due to toe scour and undercutting. This is thought to be caused by the removal of bank vegetation, and the high energy of water during high flows.

Step 5

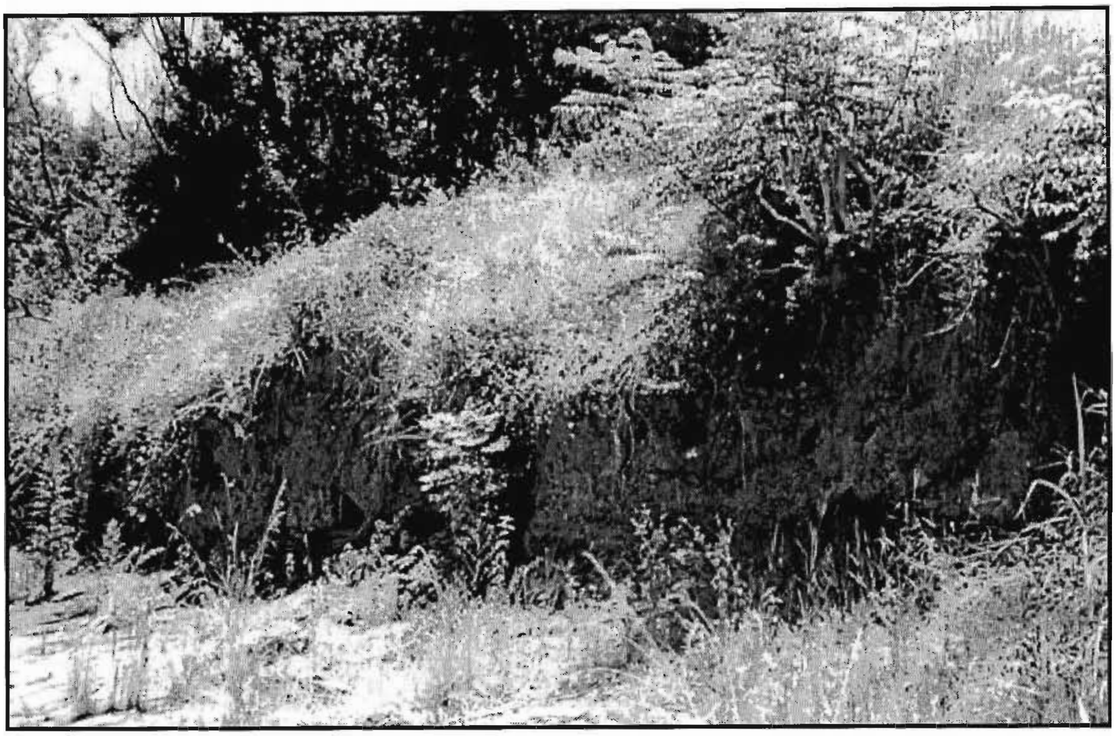
Define the rehabilitation objectives and constraints

Objectives include supporting the bank to reduce mass failure and scour. This will be supplemented by establishing suitable vegetation structure of adequate zone width and clearing alien vegetation. These objectives are constrained by available resources and land for the extension of the riparian zone width.

Step 6

Identify the rehabilitation options and concept designs

Undertake bank shaping and planting; Vegetate using vegetated geogrids; Stabilise upper bank with dormant post plantings or live stakes; Clearfell exotic species; Demarcate outer boundary of at least 8 metres from bank crest (5m + height of bank). Evaluate vegetation in the riparian zone according to over storey, under storey, ground cover and marginal cover; Derive species list from vegetation database (Table 7 and Kellner *et al.*, 2000); Plant the recommended species to the zone width.



SITE 14

Step 2

Identify and describe the problems or issues

Directly below Jesmond Road Bridge. There is a concrete lining that extends downstream (about 10 metres) from the bridge, which supports the outer bank. As the concrete lining ends, the stream makes a sharp left turn. Combined with the force acting on the outer bank (<2.5m), the extra velocity made possible by the concrete lining has severely affected the integrity of the bank. Scour has led to undercutting and mass failure and over steepening of the bank. Vegetation on the bank is also not sufficient. The bank needs structural support to resist the forces acting on it during high flows.

Step 3

Identify relevant uses and pressures

No human use at this site. Pressures include alien species invasion, removal of vegetation, the high energy environment created by the left turn and increased velocity from the concrete lining.

Step 4

Examine the stream processes and determine the causes

Insufficient vegetation on the bank, and the increased energy of the water as it passes over the concrete lining and directed onto the bank has caused undercutting leading to mass collapse and bank steepening.

Step 5

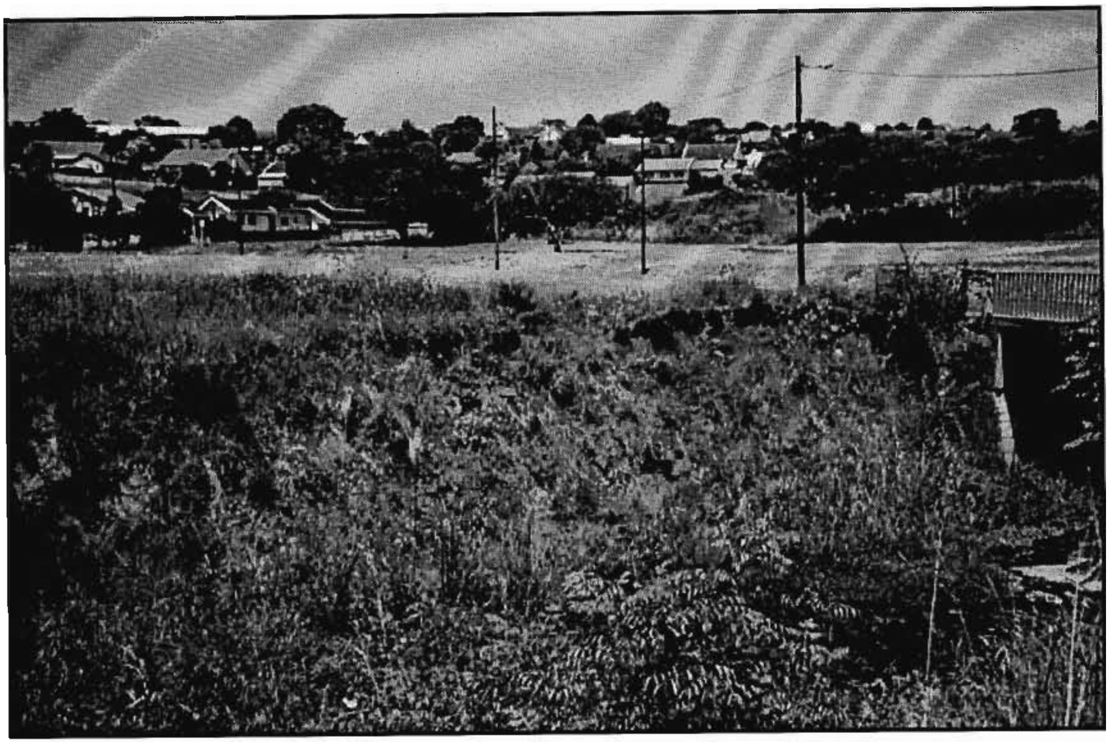
Define the rehabilitation objectives and constraints

Objectives include supporting the bank structurally and reducing the effect of erosion as water moves over the bank during high flows, establishing adequate vegetation of suitable zone width and clearing alien vegetation. Constraints include the availability of funds and land for a suitable vegetation zone width.

Step 6

Identify the rehabilitation options and concept designs

Undertake bank reshaping and planting; Apply matrass cells with joint plantings; Stabilise upper bank with dormant post plantings or live stakes; Ringbark alien trees which are fulfilling a bank stability function and remove the rest on both banks; Demarcate outer boundary of at least 7.5 metres (5m + height of bank). Evaluate vegetation in the riparian zone according to over storey, under storey, ground cover and marginal cover; Derive species list from vegetation database (Table 7 and Kellner *et al.*, 2000); Plant the recommended species to the zone width.



SITE 4

Step 2

Identify and describe the problems or issues

Directly below Andries Pretorius Road Bridge. Slumping may affect the integrity of the bridge. Structural instability is thought to be caused by the increased flow velocity on the concrete lining which undermines the bank. There is a very low presence of vegetation on the site which consists of some exotics (e.g. *Melia azedarach*).

Step 3

Identify relevant uses and pressures

No human use of this site. Pressures include the consistent mowing of vegetation around the site (although mowing promotes grass tiller development and increased basal cover, it does not give under and over storey species a chance to mature), alien vegetation, the steepness and height of the bank and energy of the water during high flows.

Step 4

Examine the stream processes and determine the causes

The dominant processes are mass soil fall and scour which are caused by a lack of suitable vegetation and the high energy state of flow during high flows. As water passes the constricted area under the bridge it moves outwards and moves in a circular motion scouring the bank, leading to over steepening and soil fall.

Step 5

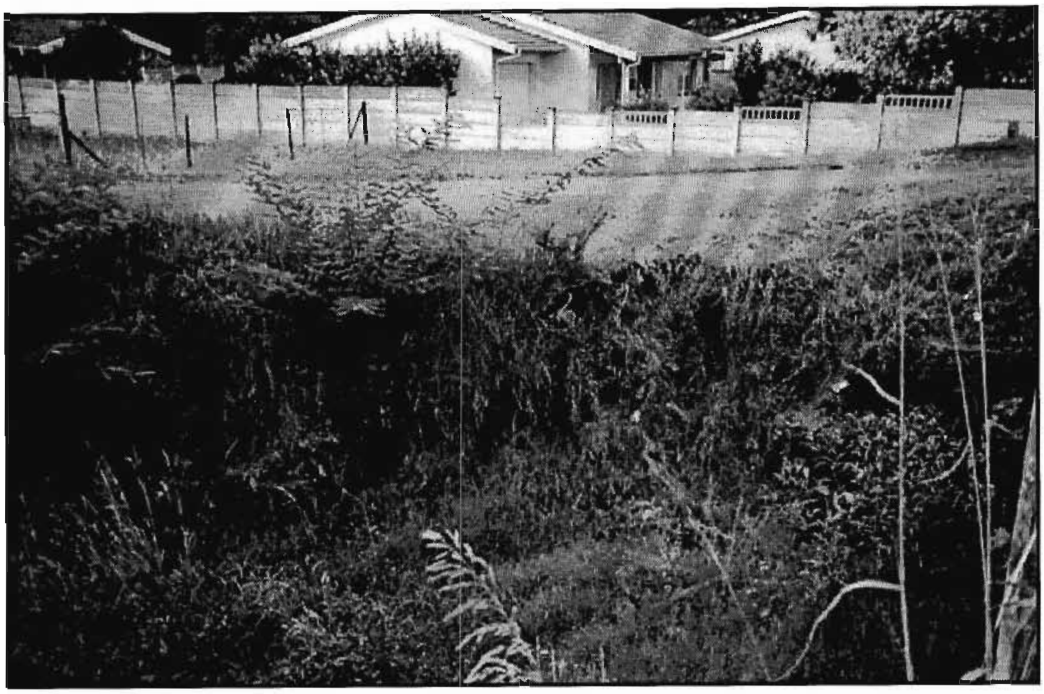
Define the rehabilitation objectives and constraints

Objectives include supporting the bank structurally and reducing the effect of erosion as water moves over the bank during high flows, establishing adequate vegetation of suitable zone width and clearing alien vegetation. Constraints include the availability of funds and land for a suitable vegetation zone width.

Step 6

Identify the rehabilitation options and concept designs

Establish live cribwalls or vegetated gabions; Stabilise upper bank with dormant post plantings or live stakes; Ringbark alien trees which are fulfilling a bank stability function and remove the rest; Demarcate outer boundary of at least 7.5 metres (5m + height of bank). Evaluate vegetation in the riparian zone according to over storey, under storey, ground cover and marginal cover; Derive species list from vegetation database (Table 7 and Kellner *et al.*, 2000); Plant the recommended species to the zone width.



SITE 8

Step 2

Identify and describe the problems or issues

Directly below Rudling Road Bridge. The integrity of the bank is supported by stone gabions, however, processes downstream of the gabions are working to undermine them and will eventually erode behind the gabions making them ineffective at stabilising the bank. Although the gabions are being undermined, they are slowing the process. What is needed is the structural reinforcement of the bank downstream from the gabions together with the establishment of vegetation. The bank is 2to2.5 metres high and >81°. Very little deep rooted vegetation occurs on the site.

Step 3

Identify relevant uses and pressures

No human use of this site. Pressures include the consistent mowing of vegetation around the site (although mowing promotes grass tiller development and increased basal cover, it does not give under and over storey species a chance to mature), alien vegetation, the steepness and height of the bank and energy of the water during high flows.

Step 4

Examine the stream processes and determine the causes

The dominant processes are mass soil fall and scour which are caused by a lack of suitable vegetation and the high energy state of flow during high flows. As water passes the constricted area under the bridge it moves outwards and moves in a circular motion scouring the bank, leading to over steepening and soil fall.

Step 5

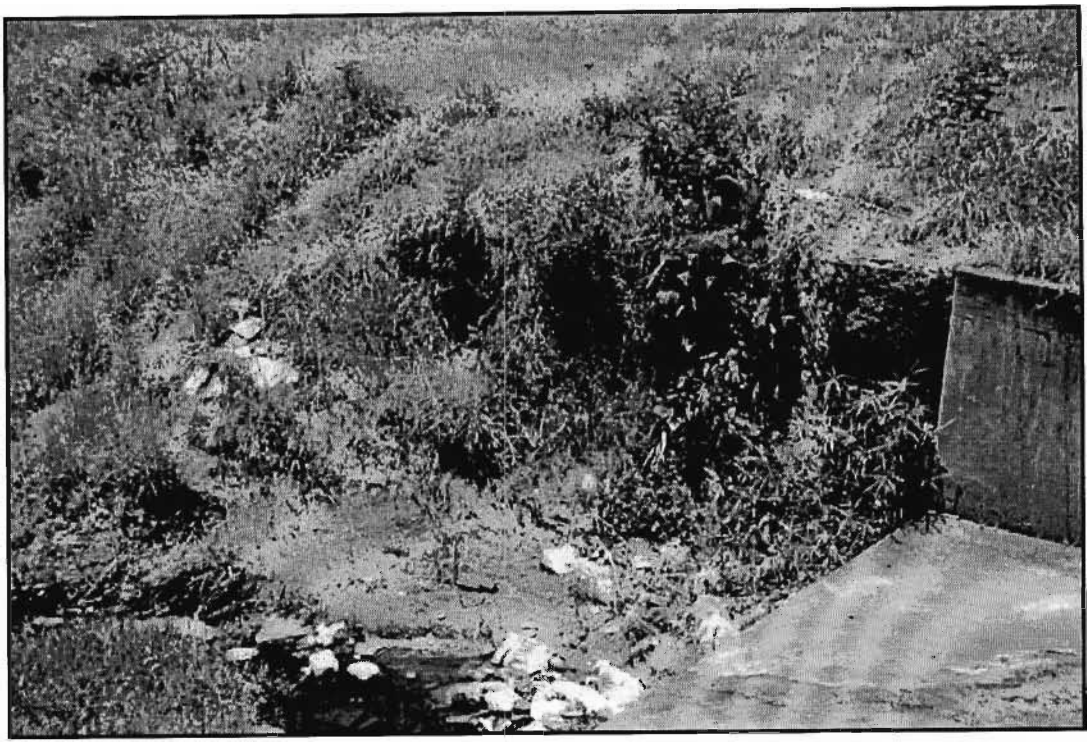
Define the rehabilitation objectives and constraints

Objectives include supporting the bank structurally and reducing the effect of erosion as water moves over the bank during high flows, establishing adequate vegetation of suitable zone width and clearing alien vegetation. Constraints include the availability of funds and land for a suitable vegetation zone width.

Step 6

Identify the rehabilitation options and concept designs

Establish live cribwalls or vegetated gabions; Stabilise upper bank with dormant post plantings or live stakes; Ringbark alien trees which are fulfilling a bank stability function and remove the rest; Demarcate outer boundary of at least 7.5 metres (5m + height of bank). Evaluate vegetation in the riparian zone according to over storey, under storey, ground cover and marginal cover; Derive species list from vegetation database (Table 7 and Kellner *et al.*, 2000); Plant the recommended species to zone width.



SITE 12

Step 2

Identify and describe the problems or issues

Bank retreat and degeneration resulting from scour that will undermine the integrity of Rudling Road Bridge in the future, are acting at this site too (see site 8). Furthermore, there is a very poor riparian vegetation community structure and all the deep rooted plants, which are juveniles, are alien. The only other vegetation on the site is grass.

Step 3

Identify relevant uses and pressures

There is residential property on the left bank, the site itself is not being used for anything. Pressures include the consistent mowing of vegetation around the site, alien vegetation, the steepness and height of the bank and energy of the water during high flows resulting from the lining of the bridge.

Step 4

Examine the stream processes and determine the causes

The dominant processes are mass soil fall and scour, which are caused by a lack of suitable vegetation and the high energy state of flow during high flows. As water passes the constricted area under the bridge it moves outwards and moves in a circular motion scouring the bank, leading to over steepening and soil fall.

Step 5

Define the rehabilitation objectives and constraints

Objectives include supporting the bank structurally and reducing the effect of erosion as water moves over the bank during high flows, establishing adequate vegetation of suitable zone width and clearing alien vegetation. Constraints include the availability of funds and land for a suitable vegetation zone width.

Step 6

Identify the rehabilitation options and concept designs

Establish live cribwalls or vegetated gabions; Stabilise upper bank with dormant post plantings or live stakes; Ringbark alien trees which are fulfilling a bank stability function and remove the rest; Demarcate outer boundary of at least 7.5 metres (5m + height of bank). Evaluate vegetation in the riparian zone according to over storey, under storey, ground cover and marginal cover; Derive species list from vegetation database (Table 7 and Kellner *et al.*, 2000); Plant the recommended species to zone width.

SITE 18

Step 2

Identify and describe the problems or issues

As with all the bridges over this stream, the Durban Road Bridge constricts the water, forcing it to speed up and so increases the energy dissipated to the banks. During high flows the banks on either side are undermined by scour which results in bank collapse and soil fall. This will eventually threaten the integrity of the bridge. The bank is 2to2.5 metres high and >81°. Vegetation is mostly alien and lacks over storey and under storey species.

Step 3

Identify relevant uses and pressures

No direct human use of this site. Pressures include the consistent mowing of vegetation around the site (although mowing promotes grass tiller development and increased basal cover, it does not give under and over storey species a chance to mature), alien vegetation, the steepness and height of the bank and energy of the water during high flows resulting from the lining of the bridge.

Step 4

Examine the stream processes and determine the causes

The dominant processes are mass soil fall and scour, which are caused by a lack of suitable vegetation and the high energy state of flow during high flows. As water passes the constricted area under the bridge it moves outwards and moves in a circular motion scouring the bank, leading to over steepening and soil fall.

Step 5

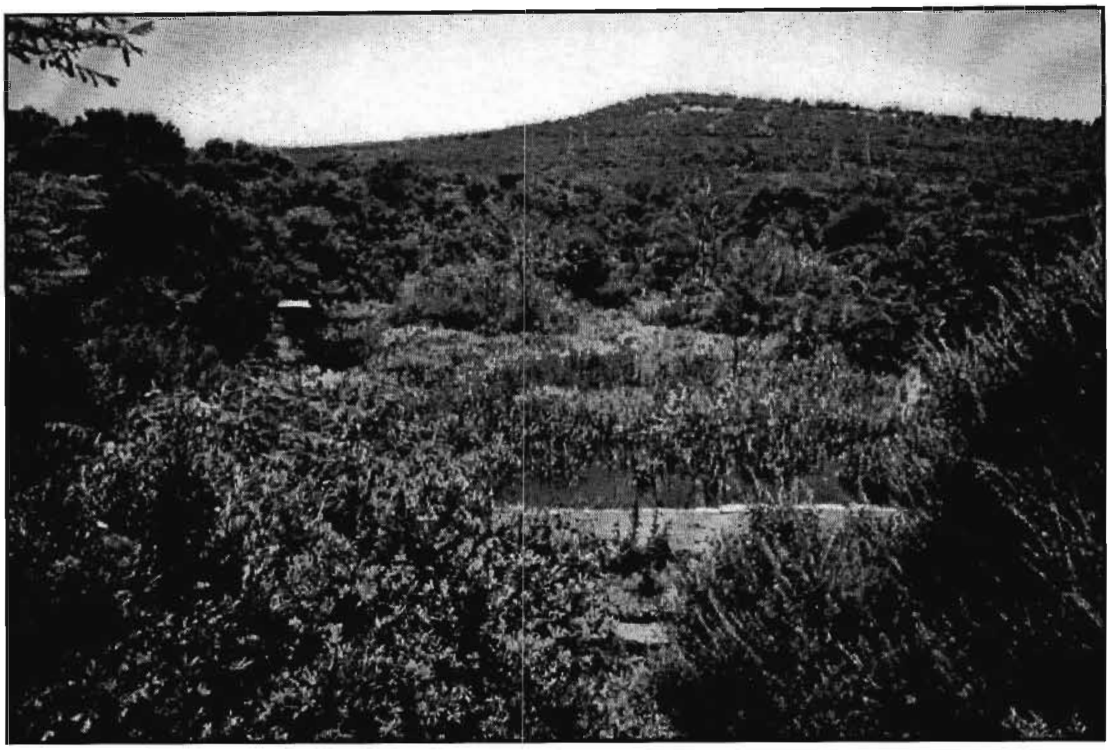
Define the rehabilitation objectives and constraints

Objectives include supporting the bank structurally and reducing the effect of erosion as water moves over the bank during high flows, establishing adequate vegetation of suitable zone width and clearing alien vegetation. Constraints include the availability of funds and land for a suitable vegetation zone width.

Step 6

Identify the rehabilitation options and concept designs

Establish live cribwalls or vegetated gabions; Stabilise upper bank with dormant post plantings or live stakes; Ringbark alien trees which are fulfilling a bank stability function and remove the rest on both banks; Demarcate outer boundary of at least 7.5 metres (5m + height of bank). Evaluate vegetation in the riparian zone according to over storey, under storey, ground cover and marginal cover; Derive species list from vegetation database (Table 7 and Kellner *et al.*, 2000); Plant the recommended species to zone width.



SITE 1

Step 2

Identify and describe the problems or issues

A stretch of river from the source to Dixon road bridge, is natural with very little modification. Its banks are stable with all structural elements of the vegetation intact and flourishing. There is very little invasion by exotic species at this site.

Step 3

Identify relevant uses and pressures

Used by humans for recreation and wild animals for grazing and access to water. There is a slight pressure resulting from some invasion by exotic species.

Step 4

Examine the stream processes and determine the causes

The presence of humans in the area has led to a slight invasion of exotic species.

Step 5

Define the rehabilitation objectives and constraints

Objectives include the removal of alien vegetation. Constraints on this activity include the availability of resources.

Step 6

Identify the rehabilitation options and concept designs

Clearfell exotic species; Evaluate vegetation in the Riparian zone according to over storey, under storey, ground cover and marginal cover; Derive species list from vegetation database (Table 7 and Kellner *et al.*, 2000); Plant the recommended species to the zone width.

SITE 2

Step 2

Identify and describe the problems or issues

Between Dixon Road Bridge and the service railway bridge. The banks are very steep but stable. The river course is mostly natural with few human interventions. There is an extremely high exotic plant invasion (>80%) and the bank verge is void of under storey vegetation, which has been cleared on both banks.

Step 3

Identify relevant uses and pressures

Upper banks are used for recreation. Pressures include extreme invasion by exotic species and smothering of flow. Clearing of the verge vegetation occurs on a frequent basis.

Step 4

Examine the stream processes and determine the causes

The influence of human pressures has led to the invasion of exotics and mowing of vegetation has led to a reduced under storey cover.

Step 5

Define the rehabilitation objectives and constraints

Objectives include the establishment of an adequate riparian vegetation structure and the elimination of exotic species. These activities are constrained by a lack of resources.

Step 6

Identify the rehabilitation options and concept designs

Clearfell exotic species; Evaluate vegetation in the riparian zone according to over storey, under storey, ground cover and marginal cover; Derive species list from vegetation database (Table 7 and Kellner *et al.*, 2000); Plant the recommended species to the zone width.

SITE 15

Step 2

Identify and describe the problems or issues

This site is approximately 200 metres downstream from Jesmond Road bridge. A human footpath, used to cross the stream has caused a gully, and if not seen to, may result in a donga.* When it rains, excess water runs down the path and into the stream, eroding the soil. Only grass is growing on the site, however, even a full complement of vegetation will not stop the problem. The people accessing the site must either be stopped or be given an alternative crossing point.

Step 3

Identify relevant uses and pressures

This site is used as a crossing point by humans. Pressures include, trampling and loosening of the soil by users, alien species invasion and runoff during wet weather.

Step 4

Examine the stream processes and determine the causes

The need to cross the stream at this site has opened a path on the bank, leading to reduced vegetation and bank gullying.

Step 5

Define the rehabilitation objectives and constraints

Objectives include reducing the impact of humans on the bank by providing better facilities and establishing suitable vegetation structure of adequate zone width. These objectives may be constrained by the lack of available resources and the willingness of humans to use alternative crossing points.

Step 6

Identify the rehabilitation options and concept designs

Human access to be managed, and the foot path to be upgraded and erosion proofed; A ford or bridge should also be built; Demarcate outer boundary of at least 7.5 metres from bank crest (5m + height of bank). Evaluate vegetation in the riparian zone according to over storey, under storey, ground cover and marginal cover; Derive species list from vegetation database (Table 7 and Kellner *et al.*, 2000); Plant the recommended species to the zone width.

* A donga is this instance is much larger version of a gully

SITE 16

Step 2

Identify and describe the problems or issues

This site is a 200 metre stretch of stream between Jesmond and Lindup Bridges. It is a relatively high energy environment, water picks up speed while flowing down a straight channelised waterway. During high flows, water undermines the toe causing bank steepening, rill and sheet erosion and minor soil fall. Vegetation on the bank lacks the under storey and most of the over storey, all of the over storey consisting of alien invasives. The bank is 2to2.5 metres high and 61°to 80°.

Step 3

Identify relevant uses and pressures

No human use at this site. Pressures include the consistent removal of vegetation, and exotic species invasion.

Step 4

Examine the stream processes and determine the causes

The channel has been artificially straightened, allowing the water to pick up speed. As a result the banks are scoured and steepened. A lack of vegetative cover, from reduced growth and clearing, further undermines bank stability, with evidence of rill and sheet erosion.

Step 5

Define the rehabilitation objectives and constraints

Objectives include reducing the impact of water on the steep banks and establishing a healthy vegetation structure or suitable zone width and clearing alien vegetation. Constraints include a lack of resources.

Step 6

Identify the rehabilitation options and concept designs

Utilise vegetated geogrids or soil filled cells; Ringbark alien trees which are fulfilling a bank stability function and remove the rest on both banks; Demarcate outer boundary of at least 7.5 metres (5m + height of bank). Evaluate vegetation in the riparian zone according to over storey, under storey, ground cover and marginal cover; Derive species list from vegetation database (Table 7 and Kellner *et al.*, 2000); Plant the recommended species to the zone width.

SITE 9

Step 2

Identify and describe the problems or issues

Site of approximately 200 metres below Rudling Road bridge which is currently stable due to the summer growth that has taken place. Once the summer growth dies back, the banks on either side will commence eroding (this has been noticed from personal knowledge of the are. The picture does not show the bank clearly enough, however if the it is examined closely, the vegetation is not as lush as it appears to be). The dominant process acting on the bank is minor rilling and soil fall resulting from a very steep bank. The banks are >2.5 metres high and >81°. The vegetation in some parts lacks an over and under storey and is invaded to some extent by exotics.

Step 3

Identify relevant uses and pressures

No direct human use of this site. Pressures include, the consistent cutting back of vegetation and the invasion by exotics. Water flowing at high velocity may also cause problems.

Step 4

Examine the stream processes and determine the causes

Lack of desired vegetative cover and presence of exotics, together with very steep banks allow water, in a high energy state, to cause degradation.

Step 5

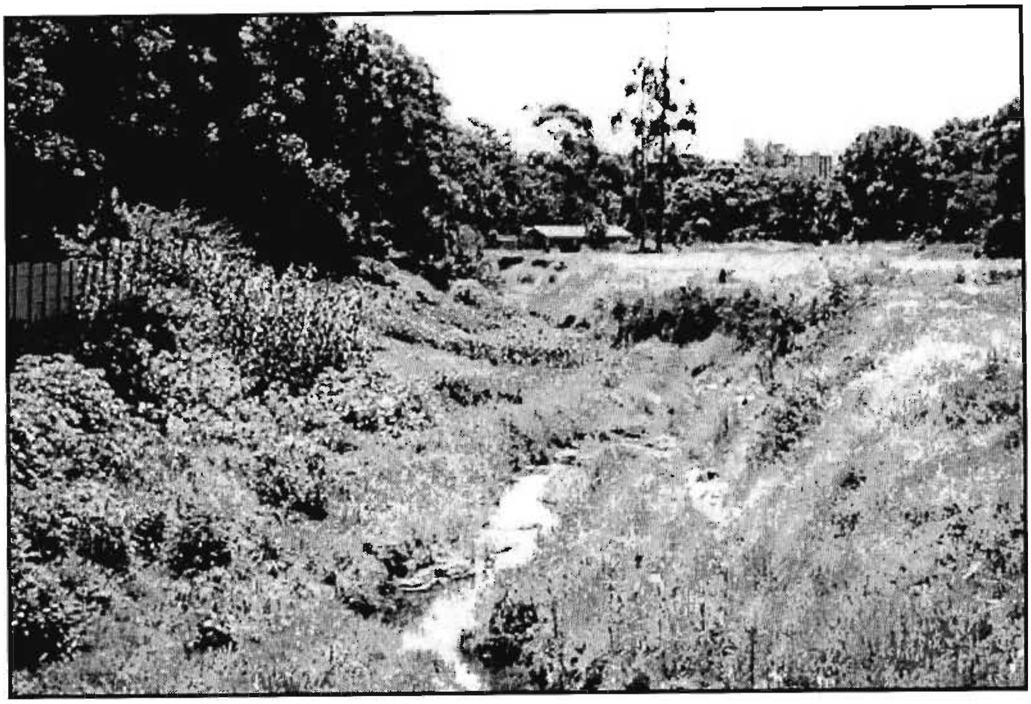
Define the rehabilitation objectives and constraints

Ease the impact of the effect of the water on the bank, establish a healthy vegetation structure on the banks, and of suitable zone width and clear alien vegetation. The objectives are constrained by a lack of resources and willingness on the part of the town council.

Step 6

Identify the rehabilitation options and concept designs

Utilise live fascines in combination with brush mattresses and a stone toe protection; Ringbark alien trees which are fulfilling a bank stability function and remove the rest; Demarcate outer boundary of at least 8 metres (5m + height of bank). Evaluate vegetation in the riparian zone according to over storey, under storey, ground cover and marginal cover; Derive species list from vegetation database (Table 7 and Kellner *et al.*, 2000); Plant the recommended species to the zone width.



SITE 13

Step 2

Identify and describe the problems or issues

Below Ritchie Road. Note two areas on the outside bend which are scoured out, undercut and resulting in mass failure. This bank is 2to2.5 metres high and >81°. The over storey and under storey are non-existent although there is a wide riparian zone. A high infiltration by exotics can be seen on the left bank. Note, the inside meander has been re-profiled and is successful, showing no signs of degradation.

Step 3

Identify relevant uses and pressures

No human use of this site. Pressures include the high velocity of the water during high flows, and mowing of the bank vegetation (although mowing promotes grass tiller development and increased basal cover, it does not give under and over storey species a chance to mature). Water is directed against the site as a result of the left turn in the stream.

Step 4

Examine the stream processes and determine the causes

Water in a high energy state is directed against the outer bend at this site. Scouring and over steepening of the bank profile has led to mass soil fall and slumping. A lack of desired vegetative cover has also contributed to the current state of the bank.

Step 5

Define the rehabilitation objectives and constraints

Protect the bank so that the full force of the water is directed against something less vulnerable, support the bank so that mass failure is prevented, clear alien vegetation and establish a healthy riparian vegetation structure of suitable zone width. Constraints include, the availability of resources and expertise to protect such a high risk area.

Step 6

Identify the rehabilitation options and concept designs

Undertake bank shaping and planting; Apply matrass cells with joint plantings; Stabilise upper bank with dormant post plantings or live stakes; ringbark alien trees which are fulfilling a bank stability function and remove the rest on both banks; Demarcate outer boundary of at least 7.5 metres (5m + height of bank). Evaluate vegetation in the Riparian zone according to over storey, under storey, ground cover and marginal cover; Derive species list from vegetation database (Table 7 and Kellner *et al.*, 2000); Plant the recommended species to the zone width.

SITE 3

Step 2

Identify and describe the problems or issues

Between service railway bridge and Andries Pretorius Road Bridge. The site is structurally sound with no signs of degradation. However, being cement lined, it performs no ecological functions. Plant growth on the upper banks low (40 to 20% cover).

Step 3

Identify relevant uses and pressures

No human use of this site. Pressures at this site include the presence of alien vegetation and channelisation of the stream.

Step 4

Examine the stream processes and determine the causes

Structural engineering of the site has prevented it from performing any ecological role. Alien vegetation has invaded the site as a result of human presence on the banks.

Step 5

Define the rehabilitation objectives and constraints

Rehabilitation objectives are to enhance the site as much as possible so as to perform ecological functions, and to remove alien vegetation and establish suitable vegetation structure and zone width.

Step 6

Identify the rehabilitation options and concept designs

Clearfell exotic species; Evaluate vegetation in the riparian zone according to over storey, under storey, ground cover and marginal cover; Derive species list from vegetation database (Table 7 and Kellner *et al.*, 2000); Plant the recommended species to the zone width. No recommendation is given about the concrete lining.

SITE 5

Step 2

Identify and describe the problems or issues

The entire area between Andries Pretorius Road Bridge and Rudling Road bridge. The site lacks an over and under storey cover, which may lead to instability (which is the case in certain parts). There is a significant presence of alien vegetation.

Step 3

Identify relevant uses and pressures

No human use of this site. Pressures include extreme invasion by exotic species and a consistent mowing of the verge vegetation (although mowing promotes grass tiller development and increased basal cover, it does not give under and over storey species a chance to mature). Bank steepness and height also pose a threat.

Step 4

Examine the stream processes and determine the causes

Clearing of vegetation has led to reduced cover and danger from bank instability. Human habitation of the area has facilitated the invasion of exotic plants.

Step 5

Define the rehabilitation objectives and constraints

Objectives include clearing alien vegetation and restoring a complete vegetation structure with suitable zone width. These objectives are constrained by the availability of resources and subject to the willingness on the part of Pietermaritzburg council.

Step 6

Identify the rehabilitation options and concept designs

Ringbark alien trees which are fulfilling a bank stability function and remove the rest; Demarcate outer boundary of at least 7.5 metres (5m + height of bank). Evaluate vegetation in the riparian zone according to over storey, under storey, ground cover and marginal cover; Derive species list from vegetation database (Table 7 and Kellner *et al.*, 2000); Plant the recommended species to the zone width using the recommended methods.

SITE 6

Step 2

Identify and describe the problems or issues

About 100 metres below Andries Pretorius Road Bridge. Site is about 50 metres long and situated on an outside meander. There is large scale degradation, the dominant process being slumping caused by undercutting. This is a high energy environment. The site lacks an over and under storey cover and there is a significant invasion by exotic species.

Step 3

Identify relevant uses and pressures

No human use of this site. Pressures include extreme invasion by exotic species, the velocity of water as it is directed against the bank and a consistent mowing of the verge vegetation. Bank steepness and height also pose a threat.

Step 4

Examine the stream processes and determine the causes

Water is directed against the outer bank during high flows scouring the bank, causing steepening, resulting in mass failure. The area is cleared of vegetation, increasing the susceptibility of the site.

Step 5

Define the rehabilitation objectives and constraints

Rehabilitation objectives include stabilising the bank so that bank scouring and slumping processes may cease, clearing alien vegetation from the site, and establishing a suitable vegetation structure with suitable zone width. Rehabilitation is constrained by resources, expertise, and higher priority to restore sites 1 to 16.

Step 6

Identify the rehabilitation options and concept designs

Undertake bank shaping and planting; Apply mattress cells with joint plantings; Stabilise upper bank with dormant post plantings or live stakes; Clearfell exotic species; Demarcate outer boundary of at least 7.5 metres from bank crest (5m + height of bank). Evaluate vegetation in the riparian zone according to over storey, under storey, ground cover and marginal cover; Derive species list from vegetation database (Table 7 and Kellner *et al.*, 2000); Plant the recommended species to the zone width.

SITE 7

Step 2

Identify and describe the problems or issues

Between Andries Pretorius Road Bridge and Rudling Road Bridge (about 50 metres above Rudling Road bridge). This site is situated at a parallel flow and seems to have been channelised artificially. Large scale slumping as a result of undercutting is the dominant process acting on banks that are about 3 metres high and > 80°. Both sides of the stream are actively eroding. Vegetation on the banks lack an over storey and under storey. There is evidence of significant alien vegetation invasion.

Step 3

Identify relevant uses and pressures

No human use of this site. Pressures include extreme invasion by exotic species and a consistent mowing of the verge vegetation. Bank steepness and height also pose a threat.

Step 4

Examine the stream processes and determine the causes

Over steepening of the bank, clearing of vegetation, scouring by water during high flows and bank height have compromised its integrity, resulting in mass failure and soil fall.

Step 5

Define the rehabilitation objectives and constraints

Rehabilitation objectives include stabilising the bank so that bank scouring and slumping processes may cease, clearing alien vegetation from the site, and establishing a suitable vegetation structure with suitable zone width. Rehabilitation is constrained by resources, expertise, and higher priority to restore sites 1to17.

Step 6

Identify the rehabilitation options and concept designs

Undertake bank shaping and planting; Apply mattress cells with joint plantings; Stabilise upper bank with dormant post plantings or live stakes; Clearfell exotic species; Demarcate outer boundary of at least 8 metres from bank crest (5m + height of bank). Evaluate vegetation in the riparian zone according to over storey, under storey, ground cover and marginal cover; Derive species list from vegetation database (Table 7 and Kellner *et al.*, 2000); Plant the recommended species to the zone width.

CHAPTER 5

Appraising Streambank Rehabilitation Decision Support System or SR-DSS

5.1 The SR-DSS process

In order to rehabilitate streambanks efficiently and effectively, a number of essentials need to be taken into account in the overall approach. Firstly, one must take a macro view of the situation. Numerous authors have advocated this and have even suggested that the haphazard rehabilitation of sites without due consideration given to priority may lead to a very much more expensive exercise (Rutherfurd *et al.*, 1999). Secondly, one needs to consider the degrading forces at work on each of the sites, remembering that addressing the causes of the problems, and not the symptoms, is central to sound streambank rehabilitation. Thirdly, one needs to take into account, all the stakeholders. Without co-operation of the people directly affected, the exercise may fail (Kondolf and Micheli, 1995). Fourthly, a sound plan of action needs to be firmly in place, for failures to be kept to a minimum and, finally, an efficient means by which appropriate rehabilitation techniques are offered needs to be sought. It is upon these essentials that the design for the system for streambank rehabilitation was based. For example, in the initial stages of the process, the user is required to inspect the catchment and identify all the sites that require rehabilitation. During this inspection, three preliminary assessment sheets are completed at each site, these being the value and threat rating sheets and the field assessment sheet. The value and threat rating sheets produce a score, which is ultimately used in the setting of priorities between sites. By doing this, the user is avoiding a haphazard approach to the rehabilitation process. This helps maximise the efficiency of the exercise. The site inspection and priority setting exercise is always the first step in the process, made obligatory through the incorporation of the eleven-step framework intended to guide the user through the rehabilitation process. By guiding the user through a series of logical steps, all the essentials cited above, are taken into account. At certain points in the exercise, such as where the choice of rehabilitation techniques needs to be made, the user is referred to the decision support system, which, through an interaction between user and SR-DSS, will yield a technique suited to the erosive forces occurring on the site, and the objective the user may have in mind.

5.1.1 Appraisal of the rehabilitation guidance process

To be confident in the recommendations given by the decision support system, a testing stage had to be incorporated into its design. The main testing segment was conducted on the Foxhill Spruit, a tributary of the Msunduzi River, which flows through the town of Pietermaritzburg. In addition to this, preliminary testing phases were carried out during the course of its development. These preliminary testing phases were done on tributaries of the Tugela River, near Tugela

Mouth in KwaZulu-Natal. The preliminary testing helped formulate and point the way for the final version of the rehabilitation model.

Owing to the small size of the Foxhill Spruit catchment, the length of the river could be inspected, and degraded sites (see glossary) rated with the field assessment sheet and priority setting model, prioritised, and given a list of techniques recommended by the decision support system. Thus, the entire process could be tested (although limited, as discussed below), from the framework through to determining the robustness of the recommendations given by the decision support system. Nevertheless, the testing process had its limitations. These limitations included the amount of time available. Without sufficient time, the process could not be thoroughly tested and the lack of financial resources prevented the implementation of the SR-DSS recommendations, which meant that the techniques could not be tested. Furthermore, the lack of a wide range of conditions, brought on by the small size of the Foxhill Spruit catchment, meant that SR-DSS could not be tested in a wide set of scenarios. Nevertheless, it includes a wider range than was provided by the Foxhill Spruit.

(i) Appraising the SR-DSS framework

The framework, within which the rehabilitation process is set, seemed to work well. It brings to the attention of the user, the dominant forces influencing each site. For example, site 15 is the location of an informal river crossing used by people. Without consideration of other factors such as willingness of humans to use alternative crossing points, a fence may have been erected at the site preventing people from crossing the stream there. Using the framework however, the author became aware that the need to cross at that particular point was created out of the convenience of the point, and humans would be unlikely to walk further to cross the stream elsewhere. The recommendation of SR-DSS therefore was adapted to suit this, and a suggestion of a bridge was made.

The testing of the framework could not be completed however, because of time and resource constraints and was only executed until step six. Steps 1 to 6 are the design phases of the rehabilitation approach, in which the sites are prioritised, and the problems, pressures, stream processes, and rehabilitation objectives and options are identified. Beyond step six, considerable detail would have been necessary, and additional information would have been required such as the execution of feasibility designs and evaluation. Steps 1 to 6, on the other hand, could be completed within the constraints and were found to place the process of prioritising, analysing and technique appraisal in a logical order. This helped simplify the process and enabled the user to set goals and limits.

(ii) Value and threat rating sheets

The gathering of data for the value and threat rating sheets and the field assessment sheet, was a simple process, and for all of the 18 sites, data capture took a total of 1½ days. Once familiar with the process, it became remarkably more efficient at the end of the exercise. No circumstances arose which were not represented on either of the sheets, although difficulty arose when it became complicated to separate one site from the next. Owing to the poor condition of the stream, degraded sites tended to stretch for considerable distances and merge with one another. It was where these sites merged with others, and different erosive processes were occurring, that it became difficult to distinguish one site from another. Changing erosive processes meant different rehabilitation techniques would be required to match each process. These challenges were overcome by separating sites into those that would require a particular rehabilitation technique. This meant, that where two sites merged over a distance of, say 10 metres, the beginning and the end of the merging sites would be taken where the dominant erosive forces changed. Furthermore, the challenge of varying conditions at one site, was overcome by taking the dominant characteristic for the field assessment sheet. A method for assessing the value of riparian areas is under development by Challen (*pers. comm.*, 2001) which may make this a more thorough process.

(iii) Field assessment sheet

All the degrading processes encountered along the Spruit's length could be scored using the field assessment sheet. It is recognised, however, that the Foxhill Spruit illustrates only a fraction of the conditions that occur along other rivers in South Africa, owing to differing conditions that occur elsewhere. For this reason, the user must proceed with caution and not take the field assessment score as an absolute assessment. Feedback is needed from users who may encounter circumstances which are not represented on the sheet, and whether there are any points of confusion. Arising from the possibility that the score may misrepresent the degradation on the site, the SR-DSS has inbuilt mechanisms to prevent this. This will be discussed below. Testing on the Foxhill Spruit, however, produced field assessment scores which represented the degradation, or problems, at the site taking into consideration the time and resource constraints associated with a project of this nature. Should these analyses be required in more detail, methods are available in the form of bank stability charts and soil analyses as discussed in Chapter 2. On the basis of the constraints subjected on the project, the field assessment sheet is judged as producing satisfactory results for what is required.

An interesting similarity exists between the scores yielded by the field assessment sheet and the value and threat rating sheets. This may be seen in Figure 17 where the field assessment scores were multiplied by a factor of 10 so that they could be compared with the priority scores. A similar trend exhibited by the two lines may be noticed. This raises the question if the field assessment sheet may be used in place of the priority setting model, where one score is reached to serve both ends. The result, in effect, would speed up the data capturing process, reducing the time spent in the field. This finding deserves further investigation, and has potential to simplify the process.

(iv) Appraising the priority setting model

The outcome of the priority setting model was in line with the general principles of priority setting that were presented in Rutherfurd *et al.* (1999). A problem identified with the priority setting process here however, is that the desired outcome is subjective. It depends greatly on the resources and objectives of the user and what he wants to achieve (different riparian managers may have a different view of what a rehabilitated system should be and look like). For this reason, the default priority was set at ecological and structural rehabilitation of the streambank at least expense, with the view that the interests of the human were central to the rehabilitation process and loss incurred, would be the most expensive result. It was thought that only once the human was satisfied (i.e. all property and buildings were out of danger), that the rest of the catchment would receive attention. The priority setting model has performed well with respect to this in that it gave priority to human interests. A problem, linked to the subjectivity of the user, is that the rules relating to the priority scores are somewhat complicated and subjectivity may arise where there is confusion over a second priority site and a third priority site. For this reason, the user must familiarise himself with the rules by studying the example provided (see Appendix 1). Furthermore, all stakeholders involved in a rehabilitation exercise need to agree on the rules. In this case, the rules should be adapted.

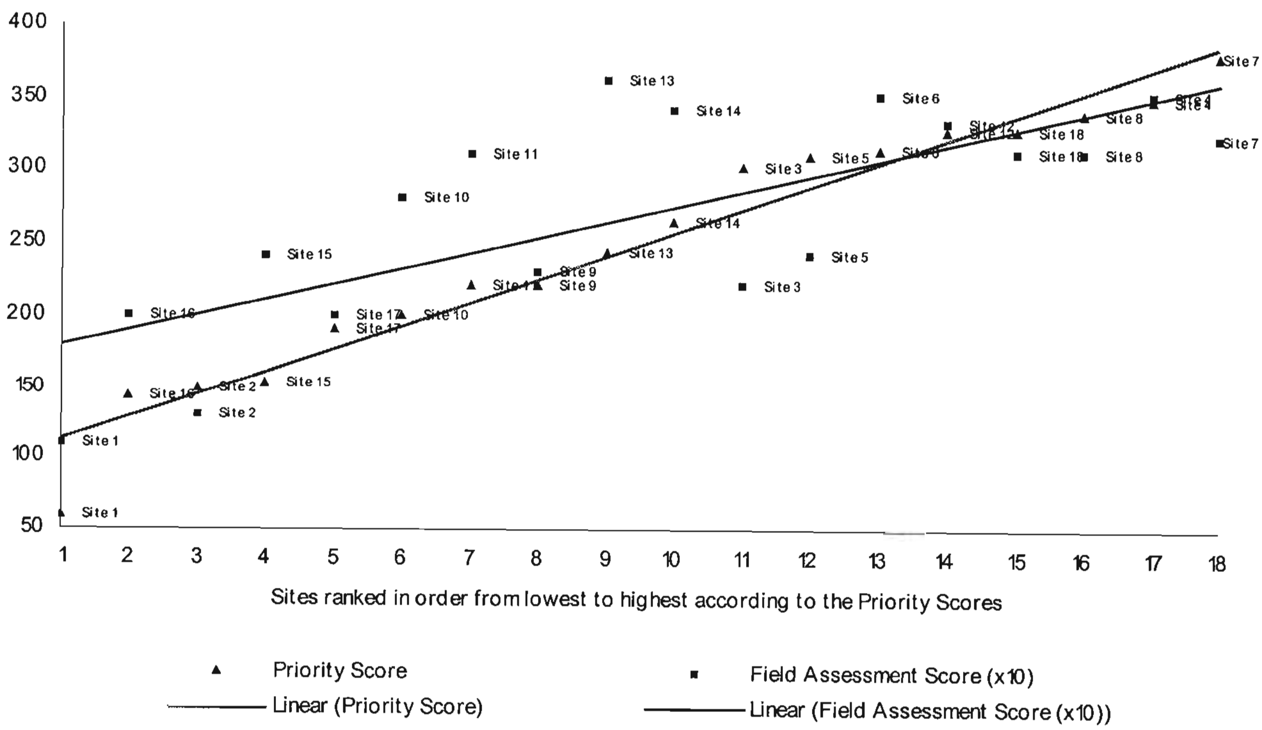


Figure 17: Graph depicting the similarity between the field assessment scores and the priority scores.

(v) SR-DSS

Based on testing on the Foxhill Spruit, it is expected that SR-DSS may be used to produce robust recommendations for similar streams in South Africa. Using this approach, a rehabilitation program may be implemented and customised to suit the user's own objectives and constraints, instead of relying on a professional who would only be available at a considerable cost. This has wider implications in that, riparian managers and conservationists are able to obtain advice at relatively low cost. SR-DSS was designed to deal with most of the problems that could be experienced in South Africa ranging from windthrow through to stock grazing and trampling damage. Those problems thought to have little effect on South African streambanks, such as the effects of freeze/thaw, have been omitted, however, these may have to be incorporated into SR-DSS for use in countries which experience those conditions, such as Lesotho where the temperature may easily drop below zero degrees Celsius. An attached appendix, lists all the techniques employed by SR-DSS, and makes available references that may be consulted for further information on each of the techniques (Appendix 2). Furthermore, where vegetative techniques are required, the user may consult Table 7 [in development by Quinn and Catherine (*pers. comm.*, 2001)], and the WRC and SAWGA indigenous species database (Kellner *et al.*, 2000).

In an attempt to test the validity of SR-DSS chosen techniques, an approval system was utilised whereby options chosen by SR-DSS were compared to other possible options that could have been recommended instead. Table 8 was produced for this purpose. This table lists all the sites requiring rehabilitation on the Foxhill Spruit against all the techniques suitable for streambank rehabilitation. The techniques chosen by SR-DSS are marked in dark blue; ones which are potential choices are marked in light blue. The reasons for not choosing the potential choices are given in a key. In each of the cases, SR-DSS recommended an appropriate technique for each site. All the potential choices have some factor advocating against them. For example site 4 was recommended live cribwalls or vegetated gabions (depending on the availability of materials) as a choice for rehabilitation. The only other options that could have been used were the bank shaping and planting option or the riprap option. Bank shaping and planting was not viable because of the high-energy environment at the site. Water would have continued to cut into the bank, therefore some form of structural support was necessary. On the other hand the riprap option may have been too expensive especially when considering the transport and access logistics involved in bringing boulders and rocks to the site. Furthermore, the revegetation of the site may have been difficult after the rehabilitation exercise due to the thickness of the rock layer that would be required. Therefore, either live cribwalls or vegetated gabions seemed the best choice. Following this testing procedure, SR-DSS was found to recommend satisfactory streambank rehabilitation techniques for matching the erosive pressures experienced on the site. At all the respective sites which needed intervention on the Foxhill Spruit, be it from exotic species invasion or large scale slumping, SR-DSS recommended techniques that would combat the problem.

Although SR-DSS has its advantages, the user must apply caution when it is being used in a number of situations. Firstly, where the degraded bank is above the height of three metres, the user is advised to consult with a structural or civil engineer. Secondly, the physical capabilities of the recommended techniques have their limitations, and must not be stretched beyond them. Their effectiveness to stabilise the bank decreases exponentially with bank height above three metres. The very nature of bank materials necessitates the use of rigid engineering methods in the region above three metres in bank height, which is the general rule of thumb (FISCRWG, 1998), although this may vary depending on a number of variables such as cohesiveness, presence of roots and moisture content.

The relative cost and difficulty of implementation also rises exponentially as the bank increases in height. Where the field assessment score above 36, the user is advised to consult with an engineer. A score of more than 36 would usually imply that the bank is extremely vulnerable, and expert advice would be required for bank stabilisation. The techniques employed by SR-DSS are not designed for extreme protection. In addition to this, the user is advised to consult an engineer if a building or structure is in serious danger of being damaged due to further bank degradation. These situations are usually high priority situations and involve large amounts of resources, an engineer would therefore be better suited in such cases.

As with the priority setting model, however, the Foxhill Spruit illustrates only a fraction of the conditions that occur in the real world, and the user must exercise caution. A fair amount of confidence is placed by the author in the SR-DSS, nevertheless, testing, or use, is needed in more diverse settings. Feedback is also needed for improvement and inclusion of circumstances that are not represented. On the basis of testing on the Foxhill Spruit however, the decision support system is able to yield sound streambank rehabilitation techniques on South African streams, provided the above concessions are observed.

Table 8: Evaluation of technique suitability by comparing the technique chosen by SR-DSS (dark blue) with an option which may have been recommended instead (light blue). The symbols within the blocks correspond with a key (below) and indicate why the option is less favourable than the SR-DSS recommendation.

	SITES																	
TECHNIQUES	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
Brush mattresses										○						○	○	
Coconut fibre roll									○									
Vegetative plants										○						○		
Branch packing									○									
Live facies																		
Stone toe protection																		
Bank shaping & pl.				■				■			□	■						■
Joint plants																		
Riprap				¶§¿•		¶§¿•	¶§¿•	¶§¿•			¶§¿•	¶§¿•	¶§¿•	¶§¿•				¶§¿
Mattress cells																		
Vegetated georgics																	○§¿	
Soil filled cells																		
Dormant post pl.																		
Live stakes																		
Live cribwalls						†	†			†			†	¶§†				
Vegetated gabions						†	†			†			†	†¶§				
Ring barking																		
Upgrade footpath																		
Clearfell exotics																		
Build bridge or ford																		

Key:

○	Insufficient support
■	Energy environment too high, needs structural support
¶	Sufficient materials may not be available
§	May be expensive
¿	May be complex
□	Technique will penetrate neighbouring property
•	May be difficult to vegetate area by using this technique
†	Will decrease the channel size further aggravating the strength of the flow

Possible option for this site

Option chosen by SR-DSS

5.2 The limitations of streambank stabilising and rehabilitation

Rehabilitation and stabilising approaches, as with all human inventions, have their limitations, the techniques presented in this document are no exception. The key is to recognise that the limitations exist, and not to stretch, or exert the techniques beyond those limitations. Financial and other resource constraints are also common to rehabilitation initiatives. Often, a set limit is defined and the project must be completed within those limits. Rehabilitation projects may be limited simply by a lack of knowledge of what the species composition was before the disturbance. Even if this information were available, the exact state of the area prior to the disturbance may be impossible to reach, simply because the conditions under which that system developed, may not be practically repeated. Besides, conditions up-stream from the site may result in permanent implications, resulting in physical forces working against the original condition of the streambanks. A lack of data may exist for a wide range of riparian areas, remembering that research costs time and money. Moreover, bank erosion mechanisms are not fully understood for all key channel types, which makes the mechanism even more difficult to diagnose. As already noted, some rehabilitation techniques may have design limitations. The key is to match the technique to the erosive force acting on the site (FISCRWG, 1998). The decision support system has been designed to match these as closely as possible. For this purpose it has been divided into sections, each dealing with an erosive force acting on the bank. Each force, would require a different approach, and a technique to match the erosive forces acting there. For example, where there is large scale degradation and comprehensive structural support is needed, the user is referred to section F of the decision support system which deals with these types of forces.

Limitations may also arise over the availability of land on the edges of the water course. These areas may be permanently occupied by residents or cultivated crops and as such will be under constant pressure. Indeed, some parcels of land in public rather than private ownership may be easier to negotiate for rehabilitation. Even in Denmark, where a law promoting water course rehabilitation was passed in 1982, obtaining land for that purpose, has proved a difficult process (Brookes, 1987; Iversen *et al.,* 1993). In more cases than not, it may be unrealistic to expect the restoration of the streambank to its original condition. Furthermore, it must be born in mind that nature is not constant. Natural areas are continually changing and adapting to altering conditions. So to attempt to replicate the condition of the bank with its pre-disturbance condition, may not only be impossible, but impractical. What should be undertaken instead, is to stabilise the bank and establish indigenous species. Once this has been achieved, the site should be left to nature as much as possible, to be modified and adapted to the changing conditions experienced on the site.

5.3 Determining streambank instability: is it local or system-wide

Although the forces that cause degradation in a stream system are problems that affect the whole catchment, it must be borne in mind that SR-DSS is essentially a site tool and cannot be used to solve problems on a broad scale. This is particularly the case in the urban setting where the drastic change in the riparian environment produces a number of problems beyond the scope of SR-DSS. For instance, the decreased percolation of water into the soil when it rains (due to increased surface area covered in hardstanding), encourages more water into the river. For this reason it may be easy for the user to loose perspective of what is being attempted by SR-DSS and the purpose of the next section is to examine this in more detail by exploring the difference between local and system-wide instabilities.

The primary diagnostic variable for differentiating between local and stream-wide channel stability problems, in a degrading stream or manufactured channel, is the stage of channel evolution. During system-wide adjustments, it usually varies systematically with distance upstream. Downstream sites might be characterised by aggradation and the waning stages of widening, whereas upstream sites might be characterised (in consecutive upstream order) by widening and mild degradation, then degradation, and if the inspection is extended far enough upstream, might be characterised by the stable, pre-disturbed condition. By using this sequence of stages, system-wide instabilities may be revealed. Stream classification can be implemented in a similar manner to natural streams. The progression of stream types may reveal system-wide instabilities (FISCWRG, 1998).

The negligence of the designers to incorporate the existing and future channel morphology into the design of rehabilitation measures often causes them to fail and, not as a result of incompetent structural design. For this reason, it is important for the designer to have a broad understanding of stream processes to guard against selected rehabilitation measures not functioning in harmony with the existing and future river conditions. This will allow the designer to evaluate whether the conditions at a particular site are due to local instability processes or are the result of some stream-wide instability that may be influencing the entire catchment (FISCWRG, 1998).

5.3.1 System-wide instability

Various factors can disrupt the equilibrium of a stream system. Once this occurs, the stream will struggle to find equilibrium by creating adjustments in the dependent variables. These adjustments, in the framework of physical processes, are generally reflected in aggradation, or changes in plan form features (meander, wavelength, sinuosity, etc.). Depending on the extent of the change and the basin characteristics (e.g. bed and bank materials, hydrology, geologic or manmade controls, sediment sources, etc.), these alterations can spread throughout the whole watershed and even into neighbouring systems. For this reason, these types of disturbance of the equilibrium condition are referred to as system-wide instability. If system-wide instability is occurring or expected to occur, it is critical that the rehabilitation measures address these problems before any bank stabilisation of instream habitat development is contemplated (FISCWRG, 1998).

5.3.2 Local instability

Erosion and deposition processes that are not indicative of a disequilibrium condition in the watershed (i.e. system-wide instability) are referred to as local instability. Conceivably the most common form of local instability is bank erosion along the concave bank in a meander bend that is occurring as part of the natural meander process. Local instability can also occur in confined locations as the result of channel constriction, flow obstructions (e.g. debris, structures, etc.), geotechnical instability, or a reduction in the vegetation on the bank. Local instability problems are responsive to local bank protection and can also exist in channels where serious system-wide instability exists. In these situations, the local instability problems will most likely be accelerated due to the system-wide instability, and a more extensive treatment plan will be obligatory. Caution must be exercised if only local treatments on one site are administered. If the upstream reach is stable and the downstream reach is unstable, a system-wide dilemma may again be displayed. The instability may persist moving upstream unless the root cause of the instability at the watershed level is eliminated or channel stabilisation at and downstream of the site is administered.

Local channel instabilities often can be accredited to redirection of flow caused by debris, structures, or the approach angle from upstream. During intermediate and high flows, impediments often result in vortices and secondary-flow cells that accelerate erosion on channel boundaries, causing local bed scour, erosion of bank toes, and ultimately bank failures. A comprehensive constriction of the channel cross section from debris accumulation or the presence of a bridge, may cause a backwater condition upstream, with a surge in the flow and scour through the constriction (FISCWRG, 1998).

It is important therefore to recognise the processes involved in the degradation. The level of intervention, and therefore the techniques that are required, will vary depending on the scale of the problem. Problems caused by system-wide instabilities are usually as a result of bad practice on the part of large groups of people e.g. bad farming practice of whole districts (it is unlikely, that system-wide instabilities would occur naturally). These problems are therefore very difficult to remedy and usually require a change in mind set on the part of groups of people. Only once the causes have been addressed, may the physical implementation of techniques commence, which would address the symptoms. It must be noted that the causes of the problems must be addressed in these cases, and only later, the symptoms. If not, the implementation of techniques, which would be at great expense, would only be a temporary measure. Local instabilities on the other hand, are usually caused by individuals, or small, groups of people who are directly involved with the site. These sites require the application of techniques where the degradation is observed. It is therefore at local instabilities that SR-DSS is aimed, because it is designed to address the problems experienced on the site, instead of attempting to change the mind set of large groups of people. It must be noted that SR-DSS is not a tool to be used in addressing problems experienced at a system-wide level, which may become a common mistake by users who are trying to solve system-wide problems by implementing local solutions. System-wide problems need to be addressed in workshops and other means where people reach agreement. SR-DSS is a tool which purely assists the user in the choice of appropriate streambank rehabilitation techniques. The actual deployment of SR-DSS is intended on a local basis where a certain problem type is being experienced on the streambank.

CHAPTER 6

Conclusions and recommendations

6.1 Principles of sound river bank rehabilitation

There are numerous documents advocating the importance of sound principles for streambank rehabilitation (Erskine and Webb, 1999; Walsh and Breen, 1999; Lucas *et al.,* 1999; Jennings and Harman, 1999; Brierley, 1999; and Watts and Fargher, 1999). Streambank rehabilitation is usually undertaken for one or more of the following reasons:

- to minimise bank erosion
- to repair or conserve riparian ecosystems and habitat
- to minimise the effect of obstructions in the channel which concentrate flows against the banks and cause erosion
- to protect endangered and/or significant species
- to restore riparian ecosystem functions
- to provide stable stream alignment
- to protect structures such as bridges and property, and,
- to arrest changes in the river course by alluvial striping

For these activities to be successful, Erskine and Webb (1999) and Lucas *et al.* (1999), recommend the following principles for sound rehabilitation.

- The assessment of the condition of the riparian area needs to take place to prioritise issues so that rehabilitation efforts may be undertaken in the most cost effective manner
- The creation of a multi-disciplinary task team to integrate hydraulics, hydrology, geomorphology and ecology in the formulation of an effective river bank rehabilitation strategy is necessary
- The goals and objectives of the rehabilitation plan, need to be established in the formal statement of intent
- Adoption of indigenous riparian species as part of the rehabilitation program is needed
- The use of an 'Adaptive Ecosystem Management' (Erskine and Webb, 1999) approach is needed to ensure that science based management actions are effectively monitored and appraised with adaptive revision of practices based on monitoring information
- Use of post-rehabilitation evaluation is needed to measure the success of a project thereby gaining essential feedback. This will enable the scientific community to build on past success, and reduce failures

Some of these principles have been recognised and integrated into the SR-DSS, however, others have been left to the user to implement. The decision to create a multi-disciplinary task team to integrate hydraulics, hydrology, geomorphology and ecology in the formulation of an effective river bank rehabilitation strategy, for example, is left for the user to decide, remembering that some degraded sites fall beyond the scope of SR-DSS. SR-DSS is able to recognise these sites and the user is made aware of them (please refer to the flow chart, part F). Where these principles can be incorporated into the design of the decision support system, this has been done. The objective of Table 9 (below) is to show how this rehabilitation approach has considered the recommendations, and incorporated them into its design.

Table 9: Shows the incorporation of the recommendations made by Erskine and Webb (1999) and Lucas *et al.* (1999) into SR-DSS.

Recommendation by Erskine and Webb (1999) and Lucas *et al.* (1999)	**How was it incorporated into SR-DSS**
The assessment of the condition of the riparian area needs to take place to prioritise issues so that rehabilitation efforts may be undertaken in the most cost effective manner	The assessment of the condition of the riparian area with the field assessment sheet and the priority setting model, is done prior to any physical rehabilitation being undertaken, so that priorities may be set and rehabilitation efforts are undertaken in the most cost effective manner.
The creation of a multi-disciplinary task team to integrate hydraulics, hydrology, geomorphology and ecology in the formulation of an effective river rehabilitation strategy	Specialists of various fields were consulted in the development of SR-DSS. Where sites fall beyond the scope of SR-DSS, the user is encouraged to seek expert advice, e.g. engineer.
The goals and objectives of the rehabilitation plan, need to be established in the formal statement of intent. The use of an 'Adaptive Ecosystem Management' (Erskine and Webb, 1999) approach is needed to ensure that science based management actions are effectively monitored and appraised with adaptive revision of practices based on monitoring information. Use of post-rehabilitation evaluation is needed to measure the success of a project against what was predicted before the project was implemented and thereby gaining essential feedback. This will enable the scientific community to build on past success, and reduce failures.	Users are encouraged to incorporate the goals and the objectives of the rehabilitation plan, in the formal statement of intent as well as to ensure that science based management actions are effectively monitored, appraised and evaluated. This is done by making the decision support system part of a model which addresses these issues. This model (see Chapter 3) is in the form of an eleven step process and addresses issues from priority setting to project monitoring, maintenance and review. The design of the decision support system, has therefore attempted to address all aspects of a sound rehabilitation plan.
The adoption of indigenous riparian species as part of the rehabilitation program needs to occur	Users are encouraged to utilise species which are not only indigenous to the country, but to the region and riparian zone in which they occur naturally.

6.2 Conclusions and recommendations

6.2.1 Conclusions

Although manuals for streambank rehabilitation have been developed (Table 1), key shortcomings have been identified. They may be inadequate for one or more of the following reasons:

- they may lack the detailed guidance that is necessary for people on the ground to understand and use. Documents that guide the process of rehabilitation, while at the same time offer possible solutions to particular problems experienced in the field are needed
- manuals which are specific to the South African situation have not been developed to date
- the information presented in some of the current available manuals is often complex and would require a fair amount of reading and understanding to obtain the information required
- none of the documents deal with how to make a decision, instead information is given and the user is left to extrapolate from what is presented.

Having noted these shortcomings it became evident that a new approach was required that would address these problems. Furthermore, a literature search suggested that decision support systems, having various qualities, have not been widely used in the field of environmental management. These qualities include (Quinn *et al.,* 1993; Kotze 1999):

- provision of cost effective solutions to managers. These solutions are based on current understanding and practice
- playing a useful role in the consolidation and evaluation of current understanding
- the possibility to explain their reasoning process in an explicit manner
- the separation of the information and inference mechanisms
- the ability to solve problems and dispense advice quickly
- the promotion of interdisciplinary collaboration and networking.

Consequently, the need for a new approach to streambank rehabilitation that would rectify the problems faced by the documents produced to date, the urgency for steps to be taken to speed the streambank rehabilitation effort in South Africa, merged with the qualities of decision support, has encouraged the development of *streambank rehabilitation decision support system* or SR-DSS. SR-DSS endeavours to effectively choose streambank rehabilitation techniques by creating an interface (i.e. flow diagrams) between the user and SR-DSS. The interface allows the exchange of information that would ultimately result in a recommendation by SR-DSS. This is customised to the objectives of the user who is given options to choose from while sufficient to match the erosive forces acting on the bank.

This ability only to recommend rehabilitation techniques was thought to be sufficient in isolated sites, however in cases where entire reaches or catchments had to be rehabilitated, a site prioritising system was necessary so that the available resources could be used in the most efficient manner. For this purpose, a priority setting model was developed and based on the principles of Rutherfurd *et al.* (1999). However, a scoring system was needed which would give a quantitative approach to the exercise. This was provided by Heron *et al.* (1999), who developed a quantitative system for setting priorities between sites. This system was adapted to comply with the principles set by Rutherfurd *et al.* (1999). To consolidate the streambank rehabilitation approach, a framework was adapted from Kapitzke (1999) that would put the rehabilitation procedure into a logical order for an holistic approach.

The rehabilitation approach was tested in the case of the Foxhill Spruit, on which 18 sites were identified that needed human intervention to regain a self sustaining natural state. This allowed testing of the framework, the priority setting model, the field assessment sheet and SR-DSS. The rehabilitation approach was found to have a number of strengths. The framework brought to the attention of the user, the dominant forces at each site, and was useful in determining the recommendation given by SR-DSS. The priority setting model allowed the 18 identified sites to be arranged in order of priority, that, according to Rutherfurd *et al.* (1999), would be the most efficient in terms of ecological value maintained and resources saved. The field assessment sheet was consistent in rating the degree of intervention required, and in each case directed the user to the appropriate sections in SR-DSS. SR-DSS recommended appropriate techniques that would match the erosive forces occurring at each site. This finding was substantiated by comparing the technique chosen by SR-DSS to techniques that may have been recommended instead (Table 8). In each case, the techniques chosen by SR-DSS were found to be superior.

The rehabilitation approach is not without its limitations however and it is these that should be focussed on in the future to allow SR-DSS to become more powerful in terms of providing advice. A lack of a wide range of conditions, brought on by the small size of the Foxhill Spruit catchment, meant that it could not be tested in a wide set of scenarios. This meant that the segments that make up the rehabilitation approach (the framework, the priority setting model, the field assessment sheet and flow charts) were not exposed to a wide range of conditions. Therefore SR-DSS may only be used with confidence on streams that are similar to the Foxhill Spruit. The individual segments had their limitations too. For example, the performance of steps 7 to 11 of the framework are unclear, owing to restrictions in time, financial and other resources, making it unviable to proceed to those stages in the framework. Furthermore, the priority setting model may be too complicated having several groups, exceptions and priority classes. The rules that determine the order of sites may need refinement in future for greater understanding by users.

A weakness of SR-DSS is that it addresses problems experienced at the site (local problems) and neglects to address the cause of those problems that may be system-wide. It attempts to solve the problem by looking for causes on a local basis, and neglects the possibility that the problems may be caused on a system-wide basis. Furthermore, the user must apply caution when SR-DSS is being used in a number of situations. Firstly, where the degraded bank is above the height of three metres, the user is advised to consult with a structural or civil engineer. Secondly, the physical capabilities of the recommended techniques have their limitations, and must not be exceeded. Their effectiveness to stabilise a bank decreases with the height of the bank above three metres. The nature of bank materials necessitates the use of rigid engineering methods (e.g. concrete lining) in the region above three metres in bank height, which is the general rule of thumb (FISCRWG, 1998), although this may vary depending on a number of variables such as cohesiveness, presence of roots and moisture content.

Another area of SR-DSS that requires refinement are the priority setting tables. Where the user is prompted to identify significant species more specific guidelines are required to make it clearer to the user what is meant by this term.

Finally and very importantly, SR-DSS has not been applied by independent users but only by its developer. Although self-scrutiny is valuable, it is not a substitute for appraisal by independent users, which is a more objective test for ease with which it can be used.

In conclusion, the user of the rehabilitation approach must remember that a well-known limitation in many rehabilitation initiatives, is that for the purposes of design, the river is considered to be unchanging in dimension, shape, and plan form. In practice, however, rivers do change, and so, an eroding bank or river bend may not necessarily indicate anthropogenic-generated instability. Therefore, the key issues to be considered are (i) recognise that river channels change either as a direct consequence of instability or of dynamic equilibrium, and (ii) understand the spatial controls on the different types of channel change. Once these issues have been acknowledged, may successful streambank rehabilitation commence.

It is believed the SR-DSS is the beginning of an approach that could be of considerable utility in riparian rehabilitation. However, as indicated by the limitations, it should be considered a stepping stone towards a more holistic approach. Several recommendations are outlined below.

6.2.2 Recommendations

- SR-DSS should only be used on streambanks that are less than three metres high, owing to the design limitations of the techniques that are recommended. Where banks are greater than three metres high, or fall outside the design limits of the rehabilitation techniques, users should consult a civil or appropriately qualified engineer.

- The similarities between the field assessment sheet and the priority setting model need to be further investigated to determine if the field assessment sheet may be used in place of the priority setting sheet adapted from Heron *et al.* (1999) as well as provide scores for SR-DSS. By using the field assessment sheet in place of the priority setting model, the process and time spent in the field would be made simpler and save time respectively. This in effect would make data capture easier by allowing the one score to serve both purposes.

- SR-DSS needs to be extended further to include all aspects of degraded rivers such as bed stabilisation, and in-stream habitat. Its potential therefore should be investigated to determine if it may be developed further into a computer-based decision support system which would make it a very powerful tool.

- Testing of the flow charts needs to occur under more diverse circumstances, as yet it has only been tested on one river with a limited number and diversity of problems.

- The field assessment sheet needs to be independently (from the flow charts) tested to ascertain its ability to measure the state of degradation on the bank. Its potential to be extended to consider other aspects of bank properties also needs to be investigated further.

- Feedback from users is critical to make improvements, adjustments and to the rehabilitation approach. This is particularly important considering that the ecological, hydro-geomorphological and management issues addressed by SR-DSS are complex, and the users for which the system is designed are primarily non-specialists.

- SR-DSS needs to be tested independently rather than just the developer of the system. This would enable valuable refinements to be made to the system.

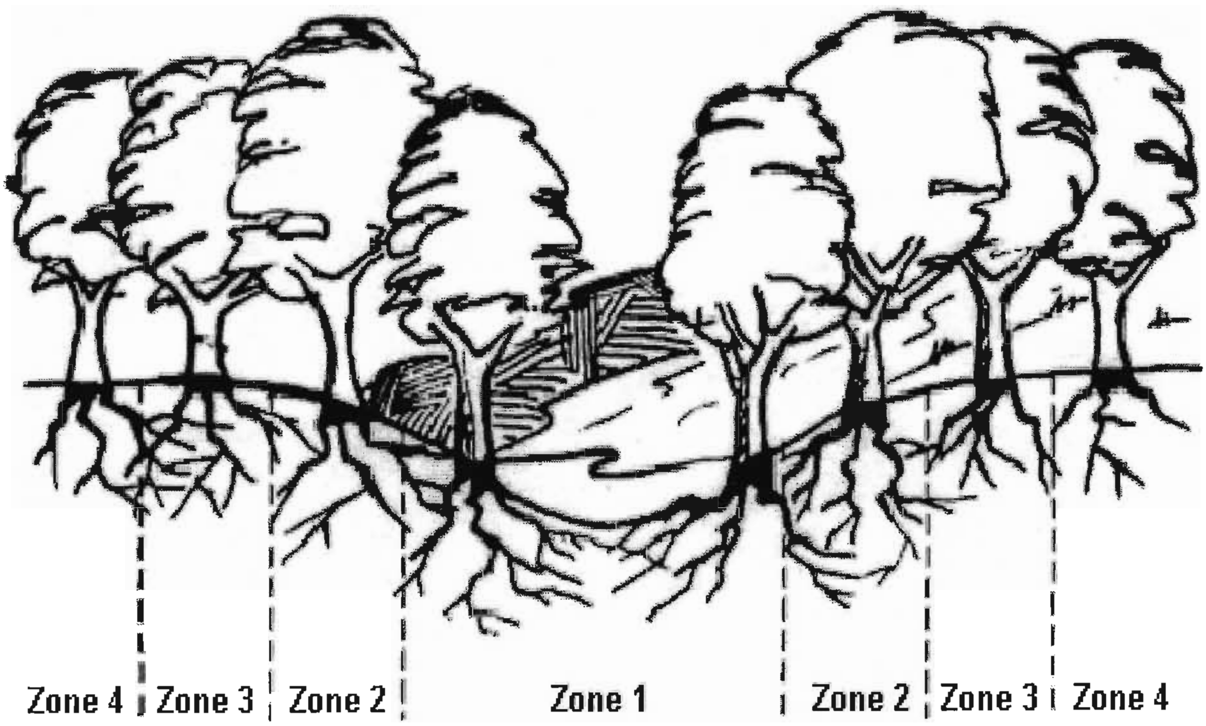
Table 7. Indigenous southern African woody species suitable for propagation (e.g. for use as live stakes, dormant post plantings, vegetative plantings, branch cuttings, branch packing etc.). Species are listed according to the biome and zone in which they are found naturally (Quinn & Catherine, *pers. comm.*, 2001). (For a complete table on recommended grass species, see Kellner *et al.,* 2000).

BIOME	POSITION IN STREAM CHANNEL / RIPARIAN ZONE - REFER TO FIGURE 18			
	Zone 1	Zone 2	Zone 3	Zone 4
SAVANNA	*Ficus natalensis*	*Acacia karroo*	*Acacia karroo*	*Bridelia micrantha*
	Ficus sycomorus	*Acacia robusta*	*Bridelia micrantha*	*Harpephyllum caffrum*
	Syzigium guineense	*Bridelia micrantha*	*Celtis africana*	*Ilex mitis*
		Cambrelum crythrophylum	*Clerodendrum glabrum*	*Macaranga capensis*
		Faidherbia albida	*Combretum erythrophyllum*	*Podocarpus latifolius*
		Ficus natalensis	*Croton sylvaticus*	*Podocarpus falcatus*
		Ficus sur	*Halleria lucida*	*Rhus chirindensis*
		Ficus sycomorus	*Harpephyllum caffrum*	*Syzygium cordatum*
		Halleria lucida	*Maesa lanceolata*	
		Harpephyllum caffrum	*Myrica pilulifera*	
		Hibiscus taliaceus	*Rhus chirindensis*	
		Ilex mitis	*Rhus lancea*	
		Macaranga capensis	*Salix mucronata*	
		Myrica pilulifera	*Trema orientalis*	
		Phoenix reclinata		
		Rauvolfia caffra		
		Rhus lancea		
		Salix mucronata		
		Syzygium cordatum		

BIOME	POSITION IN STREAM CHANNEL / RIPARIAN ZONE - REFER TO FIGURE 18			
	Zone 1	Zone 2	Zone 3	Zone 4
		Syzygium guineense		
GRASSLAND	*Ficus sur*	*Acacia karroo* *Acacia robusta* *Buddleja salviifolia* *Ficus sur* *Halleria lucida* *Hibiscus taliaceus* *Ilex mitis* *Leucosidea sericea* *Myrica pilulifera* *Phoenix reclinata* *Rhus lancea* *Rhus montana* *Salix mucronata* *Syzygium cordatum* *Syzygium guineense*	*Acacia karroo* *Buddleja salviifolia* *Celtis africana* *Clerodendrum glabrum* *Halleria lucida* *Leucosidea sericea* *Myrica pilulifera* *Rhus chirindensis* *Rhus lancea* *Rhus montana* *Salix mucronata*	*Ilex mitis* *Podocarpus latifolius* *Pododcarpus falcatus* *Rhus chirindensis* *Syzygium cordatum*

BIOME	POSITION IN STREAM CHANNEL / RIPARIAN ZONE - REFER TO FIGURE 18			
	Zone 1	Zone 2	Zone 3	Zone 4
FOREST	*Ficus natalensis* *Ficus sycomorus* *Ficus trichopoda*	*Acacia karroo* *Bridelia micrantha* *Buddleja salviifolia* *Cryptocarya latifolia* *Ficus natalensis* *Ficus sur* *Ficus sycomorus* *Ficus trichopoda* *Halleria lucida* *Harpephyllum caffrum* *Hibiscus taliaceus* *Ilex mitis* *Macaranga capensis* *Myrica pilulifera* *Rauvolfia caffra* *Salix mucronata* *Syzygium cordatum* *Syzygium guineense*	*Acacia karroo* *Bridelia micrantha* *Buddleja salviifolia* *Celtis africana* *Croton sylvaticus* *Halleria lucida* *Harpephyllum caffrum* *Maesa lanceolata* *Myrica pilulifera* *Rhus chirindensis* *Salix mucronata* *Trema orientalis*	*Bridelia micrantha* *Cryptocarya latifolia* *Harpephyllum caffrum* *Ilex mitis* *Macaranga capensis* *Podocarpus latifoilius* *Podocarpus falcatus* *Octea bullata* *Rhus chirindensis* *Syzygium cordatum*

BIOME	POSITION IN STREAM CHANNEL / RIPARIAN ZONE - REFER TO FIGURE 18			
	Zone 1	Zone 2	Zone 3	Zone 4
THICKET		*Acacia karroo* *Acacia robusta* *Ficus sur* *Rhus lancea* *Salix mucronata* *Syzygium cordatum*	*Acacia karroo* *Celtis africana* *Rhus chirindensis* *Rhus lancea* *Salix mucronata* *Trema orientalis*	*Rhus chirindensis* *Syzygium cordatum*
NAMA KAROO		*Acacia karroo* *Rhus lancea* *Rhus viminalis* *Salix mucronata*	*Acacia karroo* *Rhus lancea* *Rhus viminalis* *Salix mucronata*	
SUCCULENT KAROO		*Acacia karroo* *Rhus lancea* *Salix mucronata*	*Acacia karroo* *Rhus lancea* *Salix mucronata*	
FYNBOS		*Buddleja salviifolia* *Halleria lucida* *Ilex mitis* *Salix mucronata*	*Buddleja salviifolia* *Halleria lucida* *Rhus chirindensis* *Salix mucronata*	*Ilex mitis* *Podocarpus latifolius* *Rhus chirindensis*



VEGETATION ZONES ON STREAM CHANNEL AND BANK

ZONE 1

This zone extends from the channel proper to the edge of the riparian zone. Trees in this region usually have spreading roots that under some conditions form a root weir that may affect flow in the channel.

ZONE 2

Extends from the channel edge to the crest of the bank. Plants growing in this zone are usually vigorously rooting and are effective in bank stabilisation.

ZONE 3

Extends from the bank crest to the edge of the riparian zone. Plants growing in this zone are usually pioneer or precursor plants, that are fast growing and can tolerate full sun when young and will create partial shade for other trees and seedlings to follow.

ZONE 4

This zone forms the riparian zone edge or marginal cover. Plants that occur in this zone form the interface between the riparian vegetation and adjacent vegetation. This zone may therefore be a mix of non-riparian and riparian species.

Figure 18: Location of the different zones that occur in riparian areas (Wyatt, 1997).

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PERSONAL COMMUNICATIONS

Challen, D. Centre for Environment and Development. University of Natal, Pietermaritzburg. South Africa.

Dorian Bills. Deputy Port Engineer, Durban Harbour. Durban. South Africa

Quinne, N.W., & D. Catherine. Centre for the Environment and Development, University of Natal, Pietermaritzburg, South Africa.

APPENDIX 1

An example illustrating the use of the priority setting model, the planning and design procedure and the use of SR-DSS for a stream rehabilitation project is presented in this appendix and has been adapted in large part from Kapitzke (1999).

Consider three sites on a stream on the fringe of an urban area that is progressively developing back into the catchment with consequential stream management problems. Site 1 is a new arterial road constructed across the stream of the lower end of the catchment to service new residential developments upstream. Bank height is approximately 3 metres. Desired minimum riparian zone width is therefore 8 metres but currently is only 6 metres. The streambanks are more than 80% invaded with exotic plants, and bank stability is threatened by recreational activities such as trial bike riding and the grazing of communal cattle. Bank stability is classed as very poor. Riparian vegetation is heavily cleared and the stream bank has been graded. No threatened, rare, or significant species exist at the site.

Site 2 is an adjoining catchment which was diverted into the stream upstream of the present culvert, when a commercial area was established in the mid reaches of the catchment. The reach at site 2 has been affected in the following ways. Aggregate was extracted from the stream upstream from the site which effectively caused channelisation and straightening and cutting off of the meander bend. Severe local scour has occurred on the banks of site 2, and as a result significant undercutting exists. The stability rating of the banks is classified as poor. The vegetation on the other hand, is a mature riparian forest with all components intact and little infestation by exotics has occurred. The minimum required width (5m + 3m) is also satisfied (currently 30m).

Site 3 is upstream from site 1 and 2, and is relatively undisturbed. All components of the riparian vegetation are intact except for a slight invasion by exotics (< 10% presence). The site has more than 3 threatened, rare or significant species and exceeds the minimum riparian zone width of 9 metres and is currently 23 metres wide. To sustain these species however, the zone width needs to be increased to at least 35 metres.

The city engineer and environmental officer are charged with the responsibility of solving the problem of degradation in the stream reach. The Roads Department, who constructed the above-mentioned road and bridge, are concerned that further erosion may cause considerable damage to the structures. Residents immediately downstream of site 1 are concerned that erosion may cause loss of property. Recreational fishers, the general community and conservationists have campaigned for improved ecological and aesthetic values in the catchment. The city engineer and environmental officer have been instructed by the council to determine the most suitable method for combatting the problems presented here, and strategies for implementation. They have in the meantime learned that a catchment management strategy has been developed to guide the new residential developments in the upstream catchment. Urban stormwater management plans have also been developed to control sediment and nutrient runoff. However, these plans are vague, and are not specific enough to deal with the problems experienced at the site level.

The council will consider proceeding with the feasibility, implementation, monitoring and review phases of the projects once the priority setting and concept design phases have been completed. A simplified account of the priority setting, planning and design procedure, and SR-DSS use (steps 1 - 6) is presented below.

Step 1

Identify the most suitable sites to begin rehabilitating

To identify which site needs the most urgent attention, they must be scored, using the tables adapted from Heron *et al.* (1999). The shaded blocks indicate the state of the particular site. Once all the appropriate blocks have been marked, the scores may be computed using the formula described above. Scoring goes as follows:

Site 1

Rules for determining value rating (adapted from Heron *et al.*, 1999)

Rating	Very high	High	Moderate	Low	Very low
Value Score	1	2	3	4	5
Threatened, rare, or significant species	> 3 present	1 - 3 present	0		
Bank Vegetation	A contiguous stand of mature riparian forest established at least the recommended minimum width for its location (i.e. 5m plus the height of the bank). No alien species present.	Slightly modified, indigenous species present along both banks possibly with some grassed areas.	Significant presence of under storey exotics mixed with remnant indigenous species. Indigenous over storey generally remaining with some cleared grassed areas, or one side cleared with other virtually undisturbed.	Remnants of indigenous under storey, dominated by exotics. Ground cover mainly consists of introduced exotics.	Lacks one or more structural elements (Over storey, under storey, ground cover, or marginal cover), is in a generally degraded condition, is less than the recommended width for its location and performs no stabilising role. Consists mainly of introduced species.
Verge vegetation	A contiguous stand of mature riparian forest established at least the recommended minimum width for its location (i.e. 5m plus the height of the bank). No alien species present.	Mainly undisturbed indigenous vegetation, or some exotics or reduced cover. Minor areas of disturbance with possibly some small areas of introduced grasses.	Wide corridor of mixed indigenous and exotic species, with the one side cleared and the other reasonably undisturbed and > 5m plus the height of the bank wide.	Narrow corridor of indigenous or exotic vegetation (< 5m plus the height of the bank wide).	Both sides cleared with introduced groundcover.

Rules for determining threat rating (adapted from Heron *et al.*, 1999)

Rating	Very low	Low	Moderate	High	Very high
Threat Score	1	2	3	4	5
Bank Stability	Excellent	Good	Moderate	Poor	Very poor
Bank vegetation	A contiguous stand of mature riparian forest established at least the recommended minimum width for its location (i.e. 5m plus the height of the bank). No alien species present	Slightly modified, indigenous species present along both banks possibly with some grassed areas	Significant presence of under storey exotics mixed with remnant indigenous species. Indigenous over storey generally remaining with some cleared grassed areas, or one side cleared with other virtually undisturbed.	Remnants of indigenous under storey, dominated by exotics. Ground cover mainly consists of introduced exotics	Lacks one or more structural elements (Over storey, under storey, ground cover, or marginal cover), is in a generally degraded condition, is less than the recommended width for its location and performs no stabilising role. Consists mainly of introduced species
Verge Vegetation	A contiguous stand of mature riparian forest established at least the recommended minimum width for its location (i.e. 5m plus the height of the bank). No alien species present	Mainly undisturbed indigenous vegetation, or some exotics or reduced cover. Minor areas of disturbance with possibly some small areas of introduced grasses	Wide corridor of mixed indigenous and exotic species, with the one side cleared and the other reasonably undisturbed and > 5m plus the height of the bank wide	Narrow corridor of indigenous or exotic vegetation (< 5m plus the height of the bank wide)	Both sides cleared with introduced groundcover
Naturalness of channel	Natural	Natural with some modification (minor de-snagging or straightening)	Natural with extensive modification (major de-snagging, straightening, channel enlargement)	Constructed, un-lined	Constructed, lined
Barriers	1	2 - 5	6 - 9	10 - 15	> 16
Exotic Species	Zero infiltration	Few isolated patches on banks and verges (< 10% presence)	More frequent patches (10 - 40% presence)	Significant presence on banks and verges (40 - 80%)	Most of corridor infiltrated (> 80%)

Total Score= (sum of all values) x (sum of all threats) ∴ Total Risk = (5+5+5) x (5+5+5+3+1+5) = 360

Site 2

Total Score = (3+2+2) x (4+2+2+3+1+2) = 98

Site 3

Total Score = (1+2+2) x (1+2+2+1+1+2) = 45

Therefore, in alignment with Rutherfurd *et al.* (1999), the site with the lowest points must be prioritised. The order of priority is therefore: Site 3 (45), Site 2 (98), followed by Site 1 (360). However, as the degradation at site 1 threatens an important structure, it must take priority even though it is lowest on the priority list. Therefore, the actual order of priority, after consideration of the rules in Table 2, becomes Site 1 followed by Site 3 followed by Site 2. In this case, site 2 being upstream from site 3, would have been followed by that site in priority, had their priority scores been within 30 of each other.

Step 2

Identify and describe the problems or issues

Site 1: Problems here include a less than minimum desired riparian vegetation zone width, much of which is cleared, and alien vegetation predominates where there is vegetation. Major bank instability exists, together with a potential for infrastructural damage.

Site 2: Problems include severe local scour and resulting undercutting despite a healthy riparian vegetative structure and zone width. The channel suffers from channelisation and straightening as a result of severe bank instability.

Site 3: Slight problem of alien vegetation invasion. Although the site meets the specific site minimum riparian vegetation zone width requirement, it is not enough to sustain the rare, threatened or significant species living there.

Step 3

Identify relevant uses and pressures

Site 1: Is used by communal cattle for grazing and by bikers and fishers for recreation. An added burden is the heavy infestation by exotic plants and the intensive clearing of vegetation on the banks.

Site 2: Used for aggregate extraction, and bikers and fishers for recreation. Added pressures include flow diversion, culvert construction, urban encroachment and slight infestation by exotics.

Site 3: Has recreational value by fishers and is pressured by a slight infestation by exotics.

Step 4

Examine the stream processes and determine the causes

Site 1: Recreational biking, communal cattle grazing and clearing of vegetation have contributed to the severe infestation by exotic plants and threatened bank stability.

Site 2: Flow diversion, increased flow, and poor culvert outlet design, have combined to cause channelisation and straitening. Local scour has been caused by the increased flow and lack of vegetation to prevent it.

Site 3: Slight infestation by exotic species is most likely the result of lack of sound management principles.

Step 5

Define the remediation objectives and constraints

Site 1: Remediation objectives at this site include restoring a healthy riparian vegetation zone width to a minimum of 8 metres, reducing the prevalence of exotic species, stabilising the stream channel, and mitigating against damage caused by biking and grazing. These activities are constrained by an urgent need to repair the bank supporting the arterial road, available funds and a need to repair other sites.

Site 2: Remediation objectives should include stabilising the banks by preventing further scour and the ensuing collapse of the upper bank resulting from undercutting and eliminating the exotic species, and maintaining the vegetation zone width. The activities are constrained by a lack of funds and a higher priority for sites 1 and 3.

Site 3: The objective at this site would be to clear the area of all exotic species and widen the riparian zone width if possible. Constraints include the availability of land to increase the zone width by, and available funds.

Step 6

Identify the remediation options and concept designs

Here, SR-DSS may be used.

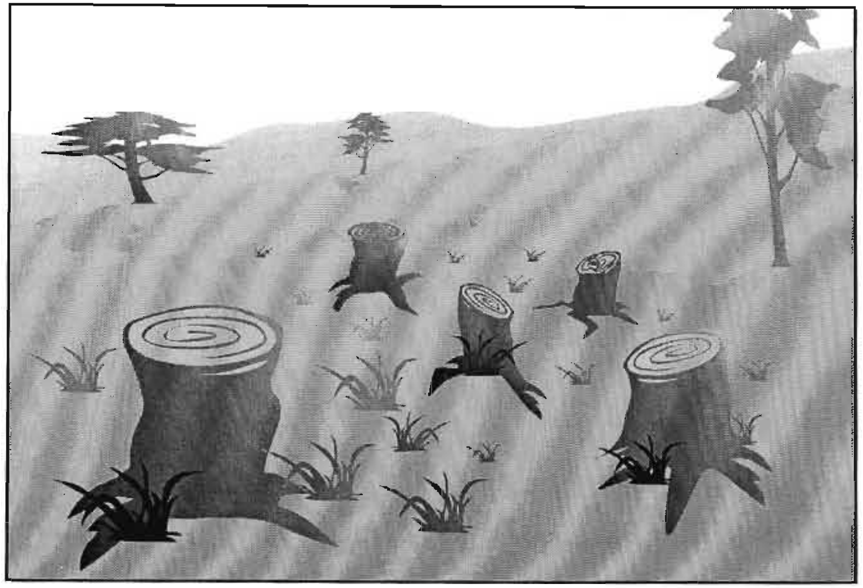
Site 1: Zone width may be increased by planting riparian species known to occur in the area (refer to Table 7 and Kellner *et al.,* 2000), to a minimum required width for that site. Care must be taken to plant species representative of all the vegetative components. Exotic species may be removed using manual labour (subject to the recommendations in SR-DSS). Stability of the bank may be restored or supported using vegetative gabions or live cribwalls (see Appendix 2). For the treatment of bank slumping, a combination of brush mattresses and dormant post plantings could be used to combat sub-aerial erosion and add extra structural support. Live stock exclusion measures should be considered to prevent harmful stock trampling. Bikers should either receive a paved pathway or be discouraged from cycling on the bank.

Site 2: Riparian zone vegetation may be treated in the same manner as above. The local scour and undercutting may be remedied by using vegetative gabions, riprap, stone toe protection or bank shaping and planting. It must be stressed that all non-vegetative rehabilitation measures must be complimented with vegetation to endure long-term success as rehabilitation ventures.

Site 3: The exotics may be removed using manual labour (subject to the recommendations in SR-DSS) and riparian vegetation width increased in the same manner as described for site 1. The operation may be paid for through the sale of cleared exotics (e.g. poles) if possible.

APPENDIX 2- Techniques appearing in SR-DSS

Technique Number 1: Clear felling



Removing plant species that are unwanted.

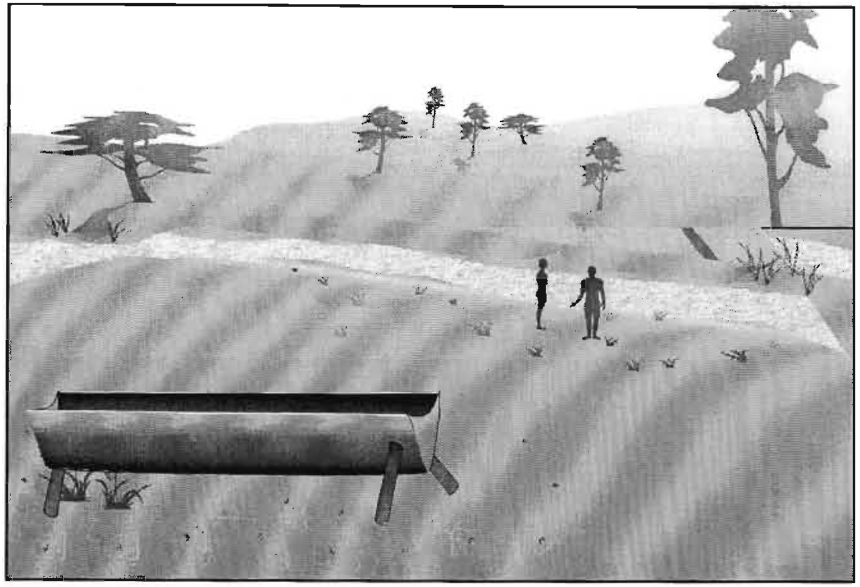
Applications and effectiveness

- Effective means of removing alien vegetation species and those that pose a threat to bank stability

For more information, consult:

1. LWRRDC. 1999. *Riparian Land Management Technical Guidelines*. Land and Water Resources Research and Development Corporation. Canberra. Australia. Vol. 1.
2. LWRRDC. 1999. *Riparian land management technical guidelines. On-ground management tools and techniques*. Land and Water Resources Research and Development Corporation. Canberra. Australia. Vol. 2.
3. Campbell, P. 2000. *Wattle control*. Plant Protection Research Institute. Pretoria. South Africa.

Technique Number 2: Stock watering troughs



Applications and effectiveness

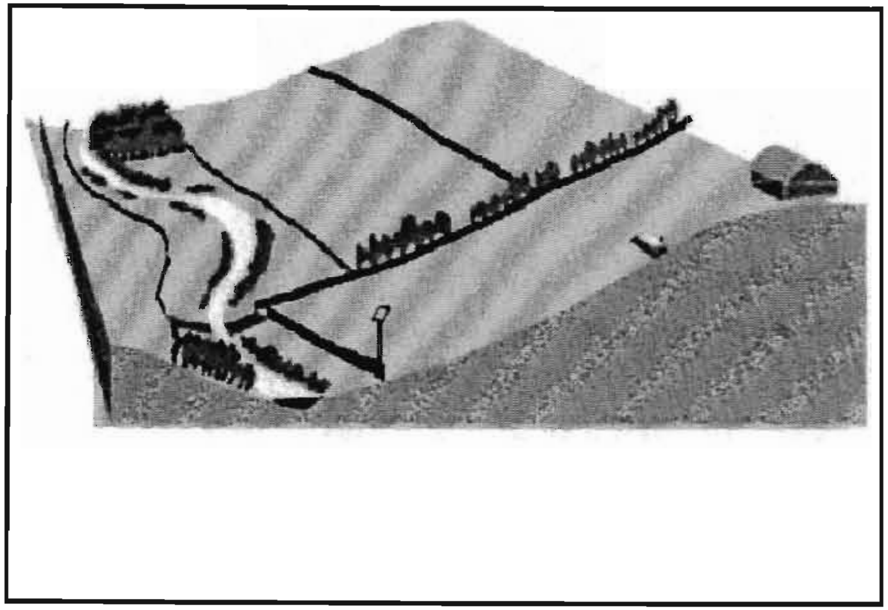
- Effective in providing stock alternative access to water
- Helps reduce the pressure exerted on the bank and the vegetation that occurs there
- Helps keep stock out of dangerous areas such as steep banks

Watering trough for stock placed away from the river in order to keep stock away from degraded or potential degradible areas on the streambank.

For more information, consult:

1. Vivash, R., & D. Murphy. 1999. *River restoration manual of techniques: Restoring the River Cole and River Skerne, UK* (1st edn.). The River Restoration Centre. UK.

Technique Number 3: Livestock / vehicle exclusion measures



Applications and effectiveness

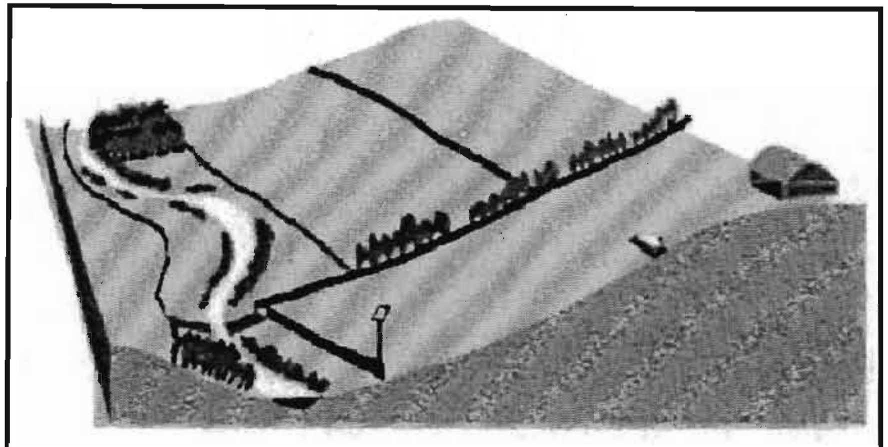
- Appropriate where livestock grazing or vehicle access is impacting negatively on the stream corridor by reducing growth of woody vegetation, decreasing water quality, or contributing to the destabilisation of streambanks
- Technique involves the total exclusion of destructive forces until such a time that the vegetation and bank stability are fully recovered

Fencing, building of alternate roads/paths and sources of water and shelter, to protect, maintain, or improve riparian flora and fauna and water quality (FISCRWG, 1998).

For more information consult:

1. Henderson, J.E. 1986. Environmental designs for streambank protection projects. *Water Resources Bulletin*. Vol. 22: 4, 549 - 558.
2. U.S. Department of Agriculture, Natural Resources Conservation Service. (Continuosly updated). National handbook or conservation practices. Washington, DC. USA.
3. LWRRDC. 1999. *Riparian Land Management Technical Guidelines*. Land and Water Resources Research and Development Corporation. Canberra. Australia. Vol. 1.
4. LWRRDC. 1999. *Riparian land management technical guidelines. On-ground management tools and techniques*. Land and Water Resources Research and Development Corporation. Canberra. Australia. Vol. 2.

Technique Number 4: Livestock / vehicle management



Applications and effectiveness

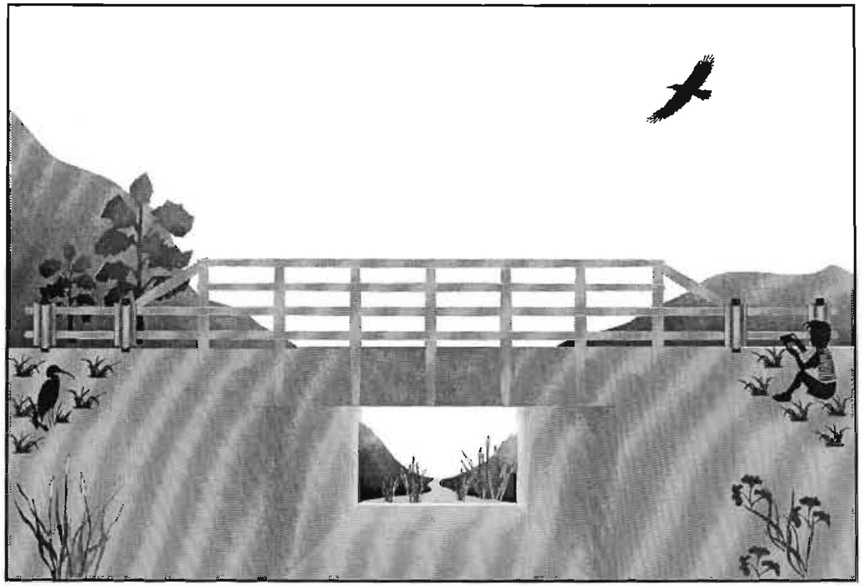
- To give the vegetation a chance to recover, grazing by stock and access by vehicles must be incorporated into an overall management plan
- Continual utilisation would force the vegetation to die back and degrade the bank further

Controlling the utilisation by stock and/or vehicles in such a manner as to give riparian vegetation a chance to recover and maintain a healthy state of growth (FISCRWG, 1998).

For more information consult:

1. National research council. 1992. Restoration of aquatic ecosystems: science technology and public policy. *National Academy Press*. Washington, DC. USA.
2. Vivash, R., & D. Murphy. 1999. *River restoration manual of techniques: Restoring the River Cole and River Skerne, UK* (1st edn.). The River Restoration Centre. UK.
3. LWRRDC. 1999. *Riparian Land Management Technical Guidelines*. Land and Water Resources Research and Development Corporation. Canberra. Australia. Vol. 1.
5. LWRRDC. 1999. *Riparian land management technical guidelines. On-ground management tools and techniques*. Land and Water Resources Research and Development Corporation. Canberra. Australia. Vol. 2.

Technique Number 5: Bridge



Applications and effectiveness

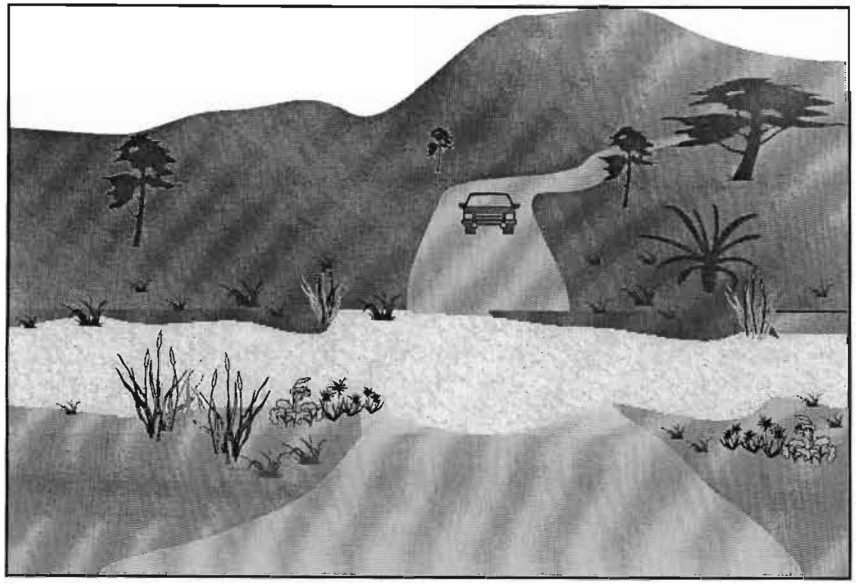
- Manageable and cost effective crossings for vehicles and stock
- Have high aesthetic value
- May be constructed from readily available pre-fabricated materials
- Its consruction may reduce the pressure resulting from continual trampling by vehicles and stock

Crossings suitable for stock and vehicle crossings, structure is used to alleviate the stresses exerted by vehicles and stock on the bank. Bridges may be constructed from pre-cast concrete boxes culverts or corrugated galvanised steel pipes amoung others. Bridges provide a cost effective means or protecting the bank.

For more information, consult:

1. Vivash, R., & D. Murphy. 1999. *River restoration manual of techniques: Restoring the River Cole and River Skerne, UK* (1st edn.). The River Restoration Centre. UK.

Technique Number 6: Ford



Applications and effectiveness

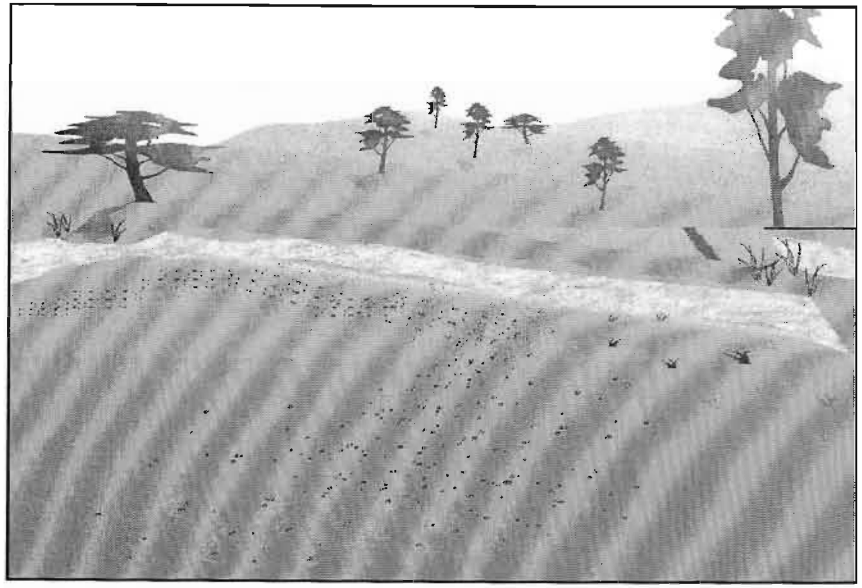
- Double as drinking areas
- Cost effective
- May be used where stock or light vehicles cross rivers or streams and so cause damage

Suitable for light vehicles and stock as a mitigation measure against trampling and bank degradation.

For more information, consult:

1. Vivash, R., & D. Murphy. 1999. *River restoration manual of techniques: Restoring the River Cole and River Skerne, UK* (1st edn.). The River Restoration Centre. UK.

Technique Number 7: Erosion proof path and upgrade



Applications and effectiveness

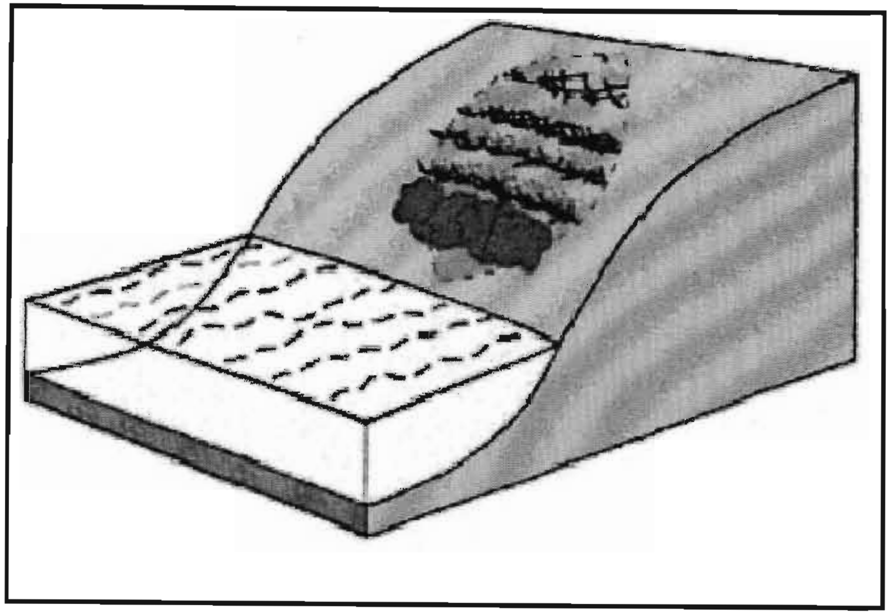
- Effective where the bank is degraded as a result of an informal path
- Erosion proofing and upgrading will attempt to deal with the problem of drainage and rainwater that runs down a bare path

The construction of a path that will allow access by users while at the same time minimise the amount of erosion and degradation occurring on the site.

For more information, consult:

1. Vivash, R., & D. Murphy. 1999. *River restoration manual of techniques: Restoring the River Cole and River Skerne, UK* (1st edn.). The River Restoration Centre. UK.

Technique Number 8: Branch packing



Applications and effectiveness

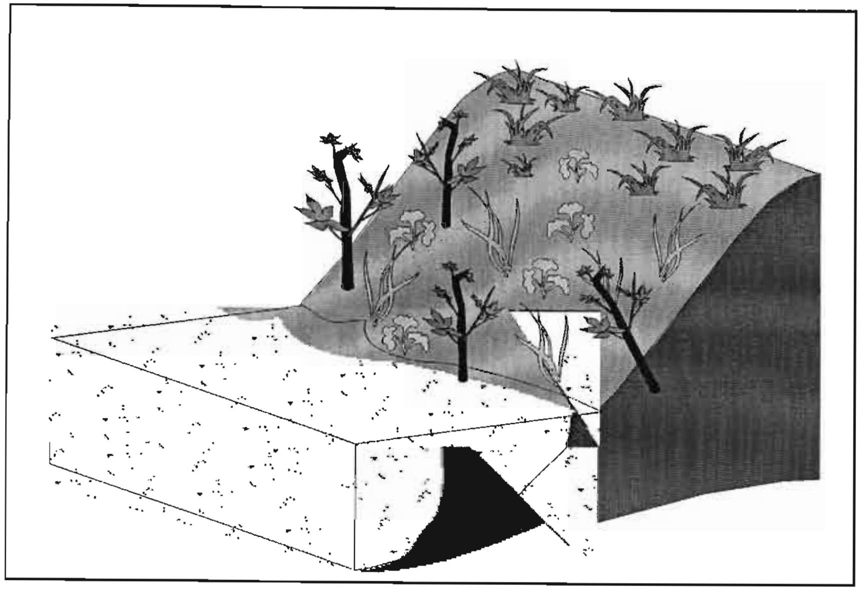
- Commonly used where patches of streambank have been scoured out and slumped, leaving a void
- Appropriate where stresses causing slump have been removed
- Produces a filter barrier that prevents erosion and scouring
- Rapidly establishes a vegetated bank
- Enhances conditions for colonisation by indigenous species
- Provides immediate soil reinforcement
- Live branches serve as tensile inclusions for reinforcement once installed
- Generally not used as a technique on its own in areas greater than 1.5 metres deep and wide

Alternate layers of live branches and compacted backfill which stabilise and revegetate slumps and holes in streambanks (FISCRWG, 1998).

For more information, consult:

1. Gray, D.H., & A.T. Leiser. 1982. *Biotechnical Slope Protection and Erosion Control.* Van Nostrand Reinhold Co. New York.
2. King County, Washington Department of Public Works. 1993. *Guidelines for bank stabilisation projects.* Seattle. USA.
3. U.S. Department of Agriculture, Natural Resources Conservation Service (USDA-NRCS). 1995 (unpublished). *Planning and design guidelines for streambank protection.* South National Technical Centre. Texas. USA.
4. U.S. Environmental Protection Agency (USEPA). 1993. *Guidance specifying management measures for sources of nonpoint pollution in coastal waters.* Publication 840-B-92-002. U.S. Environmental Protection Agency. Office of Water. Washington, D.C. USA.

Technique Number 9: Vegetative plantings



Applications and effectiveness

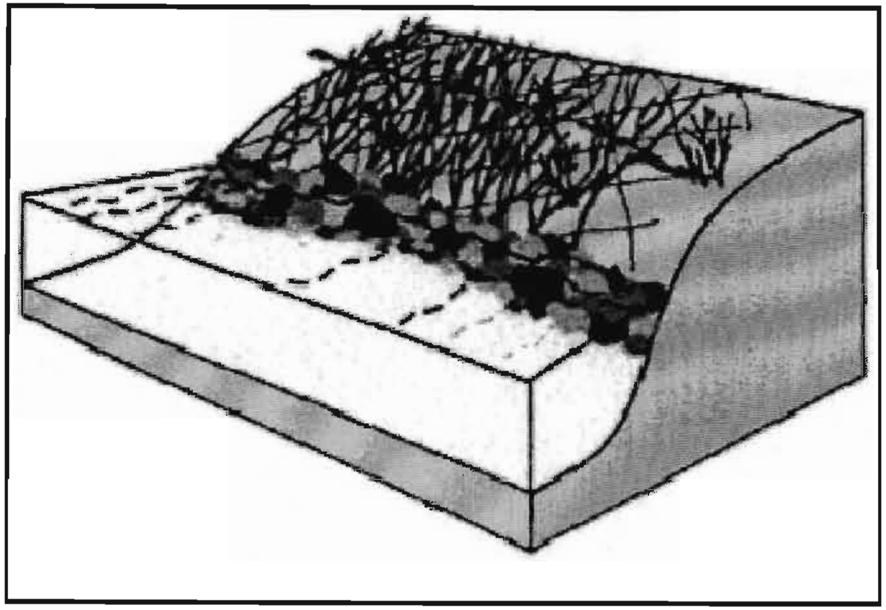
- Produces a filter barrier that prevents erosion and scouring
- Rapidly establishes a vegetated bank
- Enhances conditions for colonisation by indigenous species
- Provides immediate soil reinforcement
- Live branches serve as tensile inclusions for reinforcement once installed
- Encourages the establishment of a wide range of vegetation types, from over storey species, to grasses and marginal cover

Plantings (Table 7) of a variety of species belonging to different structural components are embedded into the channel banks to increase channel roughness and promote a variety of plant forms. Instead of planting species only of one structural component, as with dormant post plantings, tree species through to grass species are planted together.

For more information, consult:

1. Gray, D.H., & A.T. Leiser. 1982. *Biotechnical Slope Protection and Erosion Control.* Van Nostrand Reinhold Co. New York.
2. King County, Washington Department of Public Works. 1993. *Guidelines for bank stabilisation projects.* Seattle. USA.
3. U.S. Department of Agriculture, Natural Resources Conservation Service (USDA-NRCS). 1995 (unpublished). *Planning and design guidelines for streambank protection.* South National Technical Centre. Texas. USA.
4. Thompson, J.N., & D.L. Green. 1994. *Riparian restoration and streamside erosion control handbook.* Tennessee Department of Environment and Conservation. Tennessee. USA.

Technique Number 10: Brush mattresses



Applications and effectiveness

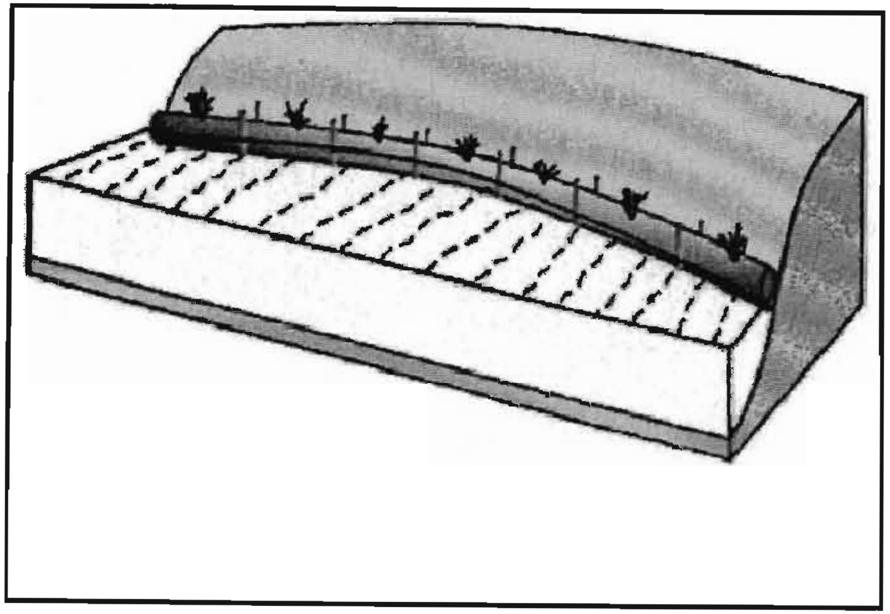
- Immediate protective cover on streambank
- Captures sediment during flood events
- Provides ideal conditions for rooting of cuttings over the streambank
- Rapidly helps to restore riparian vegetation and stream side habitat
- Enhances conditions for indigenous species colonisation
- Is limited to the slope above base flow levels
- Toe protection is required where toe scour is anticipated
- Should not be used where slopes are experiencing mass movement or other slope instability

Combination of live stakes, and branch cuttings installed to cover and physically protect streambanks; eventually to sprout and establish numerous individual plants (FISCRWG, 1998).

For more information, consult:

1. Gray, D.H., & A.T. Leiser. 1982. *Biotechnical Slope Protection and Erosion Control*. van Nostrand Reinhold Co. New York.
2. King County, Washington Department of Public Works. 1993. *Guidelines for bank stabilisation projects*. Seattle. USA.
3. Shields, F.D., & N.M. Aziz. 1992. *Knowledge based system for environmental design of stream modifications*. Applied Engineering Agriculture. ASCE. Vol. 8: 4, 553 - 562.
4. Vivash, R., & D. Murphy. 1999. *River restoration manual of techniques: Restoring the River Cole and River Skerne, UK* (1st edn.). The River Restoration Centre. UK.

Technique Number 11: Coconut fibre roll



Applications and effectiveness

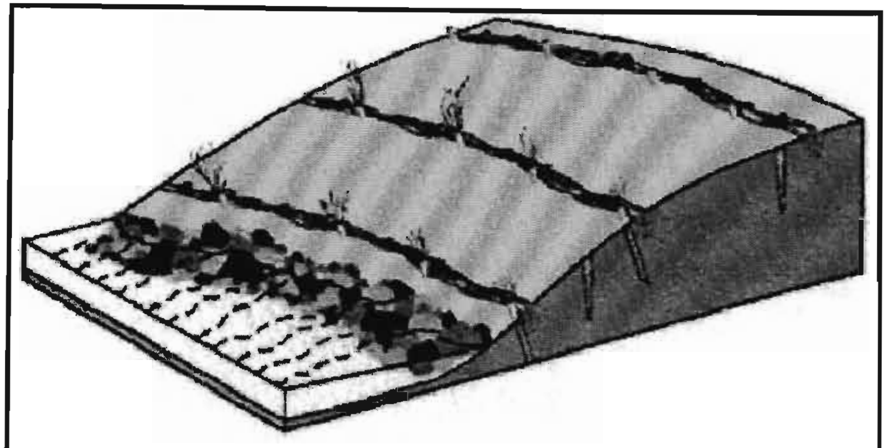
- Typically staked near the toe of the streambank with dormant cuttings and rooted plants inserted into slits cut into the rolls
- Appropriate where moderate toe stabilisation is required in conjunction
  with restoration of the streambank and the sensitivity of the site allows for only minor disturbance
- Provides an excellent medium for promoting plant growth at the water's edge and has an effective life of 6 to 10 years
- Has flexibility for moulding to the existing curvature of the streambank
- The rolls are buoyant and require secure anchoring
- Should where appropriate, be used with soil bioengineering systems and vegetative plantings to stabilise the upper bank and ensure a regenerative source of stream side vegetation

Cylindrical structures composed of coconut husk fibres bound together with twine woven from coconut material to protect slopes from erosion while trapping sediment which encourages plant growth within the fibre roll (FISCRWG, 1998).

For more information, consult:

1. Thompson, J.N., & D.L. Green. 1994. *Riparian restoration and streamside erosion control handbook*. Tennessee Department of Environment and Conservation. Tennessee. USA.
2. U.S. Department of Agriculture, Natural Resources Conservation Service (USDA-NRCS). 1996. Streambank and shoreline protection. In *Engineering Field Handbook*. Part 650, Chapter 16.

Technique Number 12: Live fascines



Applications and effectiveness

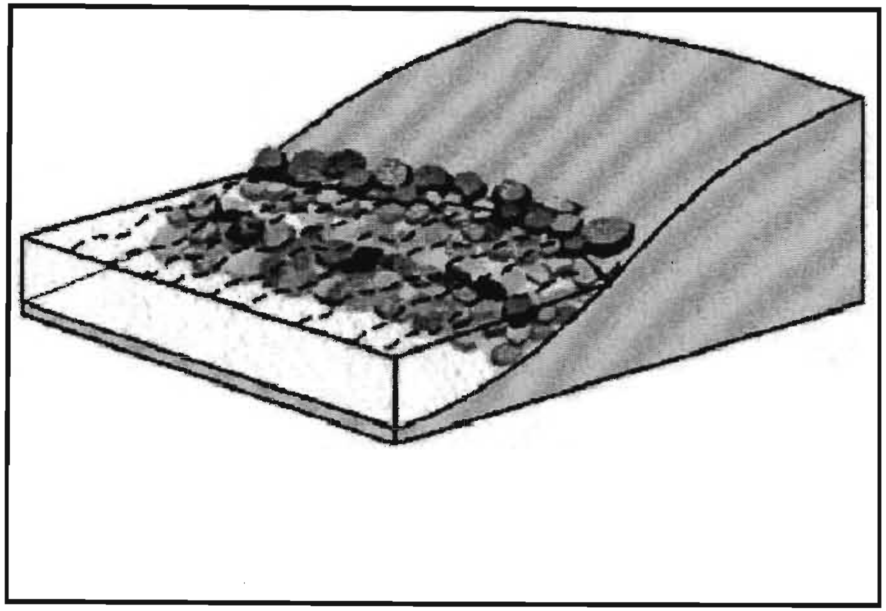
- Traps and holds soil on the streambank by creating small dam-like structures and reducing the slope length into a series of shorter slopes
- Facilitates drainage when installed at an angle on the slope
- Enhances conditions for indigenous species colonisation
- Should be used with other soil bioengineering techniques and vegetative plantings
- Requires toe protection where scour is anticipated
- Not appropriate for slopes undergoing mass movement
- Effective stabilisation technique for slopes requiring minimum site disturbance

Dormant branch cuttings bound together into long sausage like, cylindrical bundles and placed in shallow trenches on slopes to reduce erosion and shallow sliding (FISCRWG, 1998).

For more information, consult:

1. Gray, D.H., & A.T. Leiser. 1982. *Biotechnical Slope Protection and Erosion Control*. Van Nostrand Reinhold Co. New York.
2. King County, Washington Department of Public Works. 1993. *Guidelines for bank stabilisation projects*. Seattle. USA.
3. Thompson, J.N., & D.L. Green. 1994. *Riparian restoration and streamside erosion control handbook*. Tennessee Department of Environment and Conservation. Tennessee. USA.
4. U.S. Department of Agriculture, Natural Resources Conservation Service (USDA-NRCS). 1996. Streambank and shoreline protection. In *Engineering Field Handbook*. Part 650, Chapter 16.

Technique Number 13: Stone toe protection



Applications and effectiveness

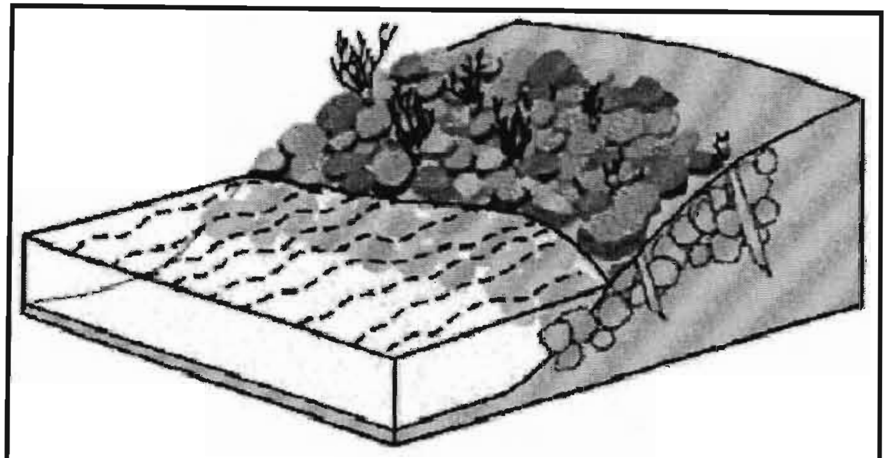
- Applicable where banks are being undermined by toe scour, and where vegetation cannot be used
- Stones prevent removal of failed streambank material that collects at the toe, promotes revegetation and stabilises the bank
- Should be used with other soil bioengineerining systems and vegetative plantings to stabilise the upper bank and ensure a regenerated source of stream side vegetation
- Can be placed with minimal disturbance to existing slope, habitat and vegetation

A ridge of quarried rock or stream cobble placed at the toe of the streambank as an armour to deflect flow from the bank, stabilise the slope and promote sediment deposition (FISCRWG, 1998).

For more information, consult:

1. DuPoldt, C.A. 1996. *Compilation of technology transfer information from the XXVII conference of the International Erosion Control Association.* U.S. Department of Agriculture. Natural Resources Conservation Service. Somerset. USA.
2. King County, Washington Department of Public Works. 1993. *Guidelines for bank stabilisation projects.* Seattle. USA.
3. U.S. Army Corps or Engineers. 1981. Main report, Final report to congress on the streambank erosion control evaluation and demonstration Act of 1974, Section 32, Public Law 93-251. U.S. Army Corpes of Engineers, Washington, DC. USA.
4. Vivash, R., & D. Murphy. 1999. *River restoration manual of techniques: Restoring the River Cole and River Skerne, UK* (1st edn.). The River Restoration Centre. UK.

Technique Number 14: Joint plantings



Applications and effectiveness

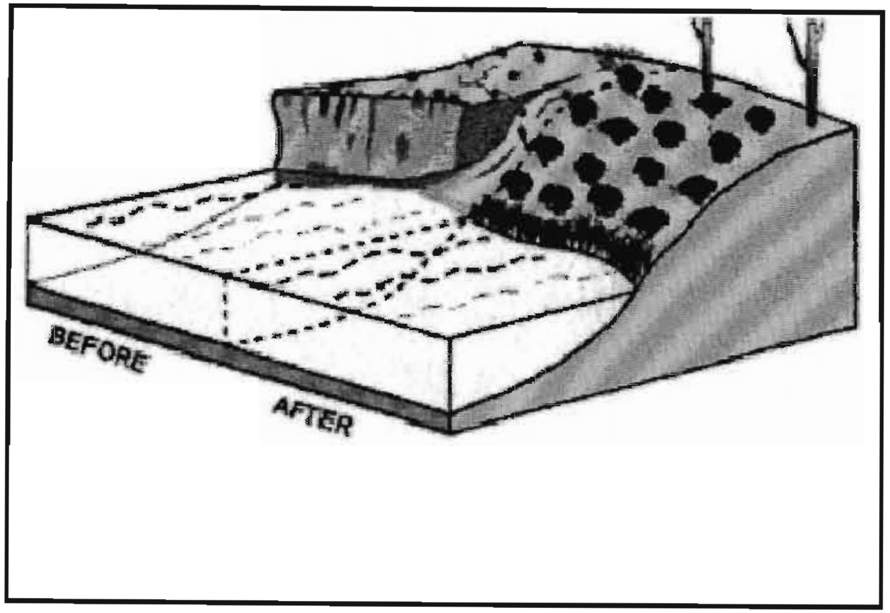
- Appropriate where there is a lack of desired vegetative cover on the face of existing or required rock riprap
- Root systems provide a mat upon which the rock riprap rests and prevents loss of fines from the underlying soil base, and also improves drainage
- Will quickly establish vegetation and enhance conditions for indigenous species colonisation
- Have few limitations and can be installed from base flow levels to the top of the slope, if live stakes ae installed to reach ground water
- Thick rock riprap layers may require special tools for establishing pilot holes

Vegetative plantings, usually live stakes(see Table 7 for species list), trampled into joints or openings between rock which have previously been installed ona slope or while rock is being placed on the slope (FISCRWG, 1998).

For more information, consult:

1. King County, Washington Department of Public Works. 1993. *Guidelines for bank stabilisation projects*. Seattle. USA.
2. Thompson, J.N., & D.L. Green. 1994. *Riparian restoration and streamside erosion control handbook*. Tennessee Department of Environment and Conservation. Tennessee. USA.
3. U.S. Department of Agriculture, Natural Resources Conservation Service (USDA-NRCS). 1996. Streambank and shoreline protection. In *Engineering Field Handbook*. Part 650, Chapter 16.
4. U.S. Environmental Protection Agency (USEPA). 1993. *Guidance specifying management measures for sources of nonpoint pollution in coastal waters*. Publication 840-B-92-002. U.S. Environmental Protection Agency. Office of Water. Washington, D.C. USA.

Technique Number 15: Bank shaping and planting



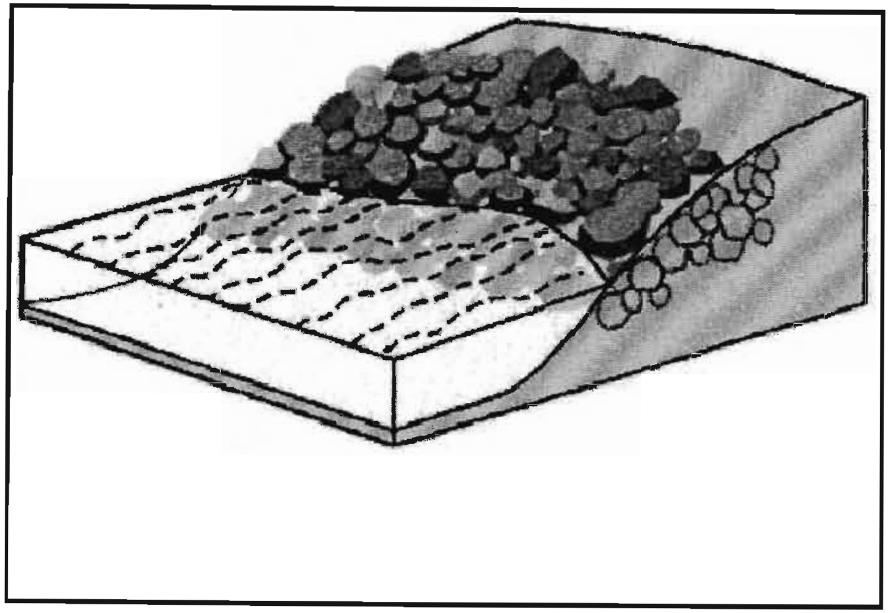
Applications and effectiveness

- Reinforcement at the toe is often needed
- Used in conjunction with other protective practices where flow velocities exceed the tolerance range for available plants, and where erosion occurs below base flows
- Streambank soil materials, probable groundwater fluctuation, and bank loading conditions are factors for determining appropriate slope conditions
- Slope stability analyses may be required

Regrading streambanks to a stable slope, placing topsoil and other materials needed for sustaining plant growth, and selecting, installing and establishing appropriate plant species (FISCRWG, 1998).

For more information, consult:

1. Flosi, G., & F. Reynolds. 1991. *California salmonid stream habitat and restoration manual*. California Department of Fish and Game. USA.
2. Gray, D.H., & A.T. Leiser. 1982. *Biotechnical Slope Protection and Erosion Control*. Van Nostrand Reinhold Co. New York.
3. Shields, F.D., & N.M. Aziz. 1992. Knowledge based system for environmental design of stream modifications. *Applied Engineering Agriculture*. ASCE. Vol. 8: 4, 553 - 562.
4. U.S. Department of Agriculture, Natural Resources Conservation Service (USDA-NRCS). 1996. Streambank and shoreline protection. In *Engineering Field Handbook*. Part 650, Chapter 16.



Applications and effectiveness

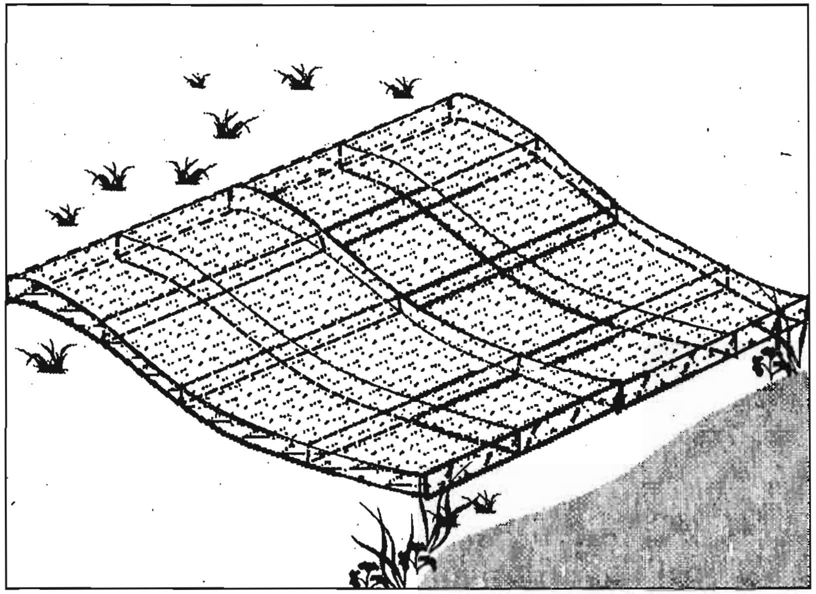
- May be vegetated
- Appropriate where longterm durability is needed, design discharges are high, and there is a significant threat to life or high value property, or there is no practical way to otherwise incorporate vegetation into the design
- Flexible and not impaired by slight movement from settlement or other adjustments
- Can be expensive if materials are not locally available

A blanket of appropriately sized stones extending from the toe of the slope to a height needed for long term durability (FISCRWG, 1998).

For more information, consult:

1. Flosi, G., & F. Reynolds. 1991. *California salmonid stream habitat and restoration manual.* California Department of Fish and Game. USA.
2. Gray, D.H., & A.T. Leiser. 1982. *Biotechnical Slope Protection and Erosion Control.* Van Nostrand Reinhold Co. New York. USA.
3. Henderson, J.E. 1986. Environmental designs for streambank protection projects. *Water Resources Bulletin.* Vol. 22: 4, 549 - 558.
4. U.S. Department of Agriculture, Natural Resources Conservation Service (USDA-NRCS). 1996. Streambank and shoreline protection. In *Engineering Field Handbook.* Part 650, Chapter 16.

Technique Number 17: Geotextile Mattress/cells



Applications and effectiveness

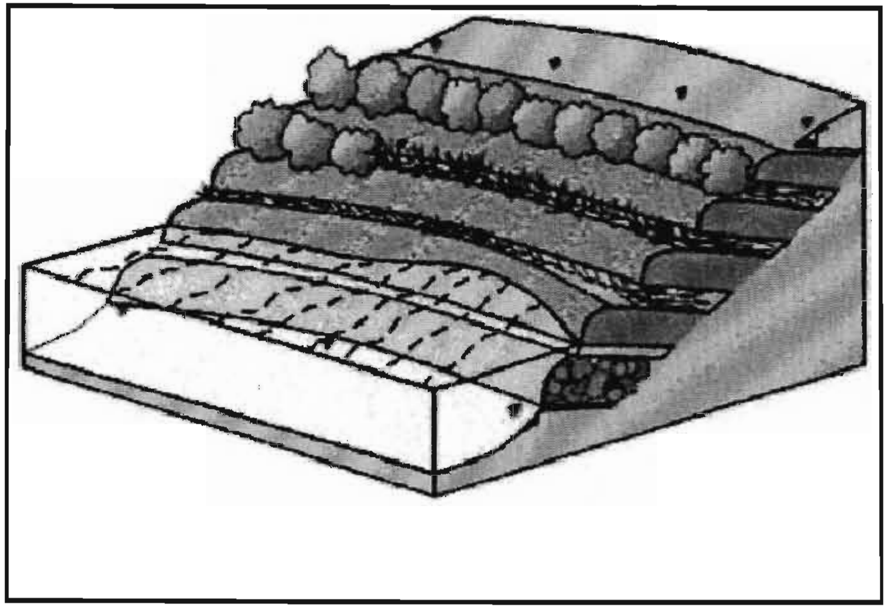
- Effective for depositional environments
- Slows the passage of water and allows deposition to occur
- Promotes establishment of indigenous vegetation
- A range or combination of different materials such as stones, soil, or vegetative cuttings may be used depending on the objectives of the user

Structure promotes the slowing of water through the stone fill and will facilitate the deposition of soil in the interstices and indigenous vegetation will colonise the structure spontaneously.

For more information, consult:

1. African Gabions, available online: www.africangabions.co.za.

Technique Number 18: Vegetated geogrids



Applications and effectiveness

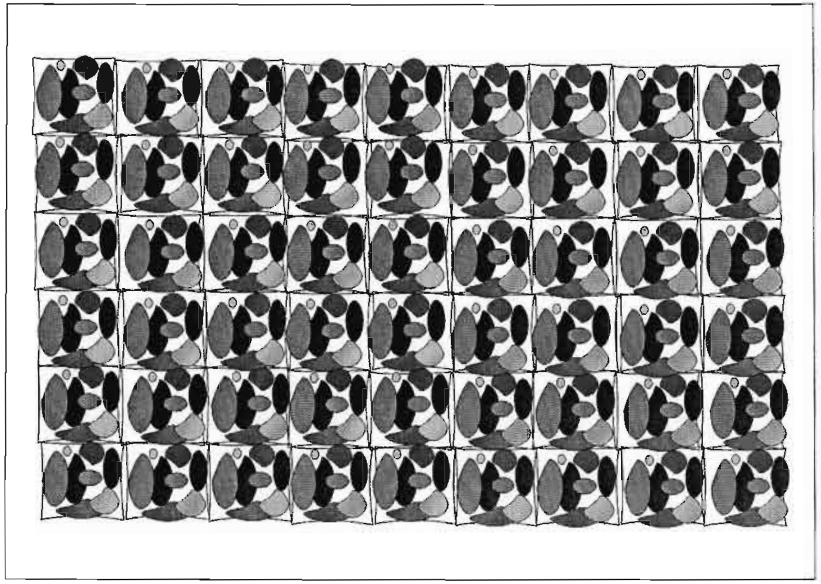
- Can be used to quickly establish riparian vegetation if properly installed
- May be installed on a steeper and higher slope and has a higher iniial tolerance of flow velocity than brush layering
- Produces a newly constructed, well reinforced bank
- Useful in restoring outside bends where erosion is a problem
- Captures sediment and enhances conditions for indigenous species colonisation
- This technique requires a stable foundation and stability analyses may be required

Alternating layers oF live branch cuttings and compacted soil with natural or synthetic geotextile materials wrapped around each soil lift to rebuild and vegetate eroded streambanks (FISCRWG, 1998).

For more information, consult:

1. DuPoldt, C.A. 1996. *Compilation of technology transfer information from the XXVII conference of the International Erosion Control Association.* U.S. Department of Agriculture. Natural Resources Conservation Service. Somerset. USA.
2. Flosi, G., & F. Reynolds. 1991. *California salmonid stream habitat and restoration manual.* California Department of Fish and Game. USA.
3. Gray, D.H., & A.T. Leiser. 1982. *Biotechnical Slope Protection and Erosion Control.* Van Nostrand Reinhold Co. New York.
4. King County, Washington Department of Public Works. 1993. *Guidelines for bank stabilisation projects.* Seattle. USA.

Technique Number 19: Soil filled cells



Applications and effectiveness

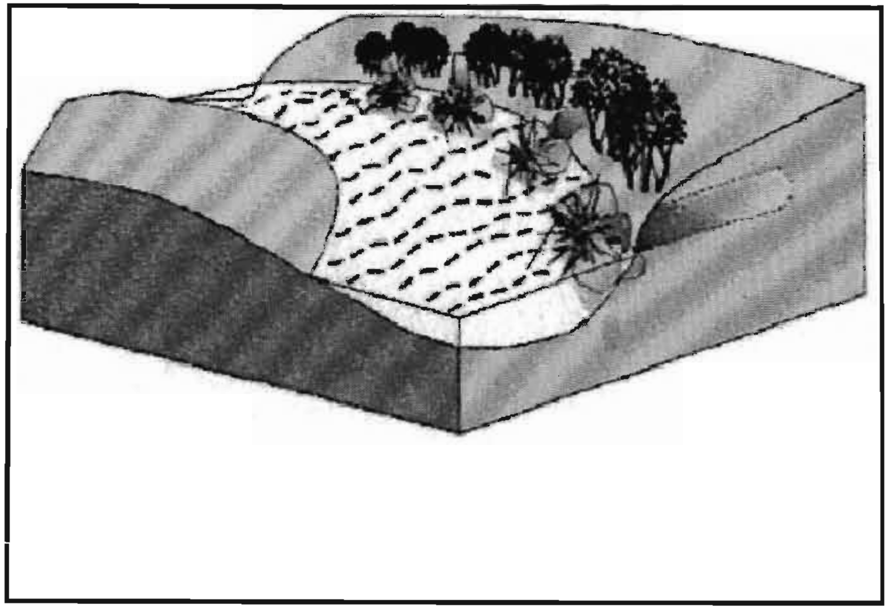
- Suitable for topsoil retention
- Flexible structure
- Improves the stability of the top layer and prevents surface slip
- Forms mini-cascades, which slow down surface run-off and prevents the formation of gullies

A cellular structure made by alternate linking of strips of select geotextile.
The strips are stitched together forming square cells and should be filled either with earth, gravel or concrete.

For more information, consult:

1. Kaytech Geosynthetics. Available online: www.kaymac.co.za.

Technique Number 20: Log, rootwad, and boulder revetments



Applications and effectiveness

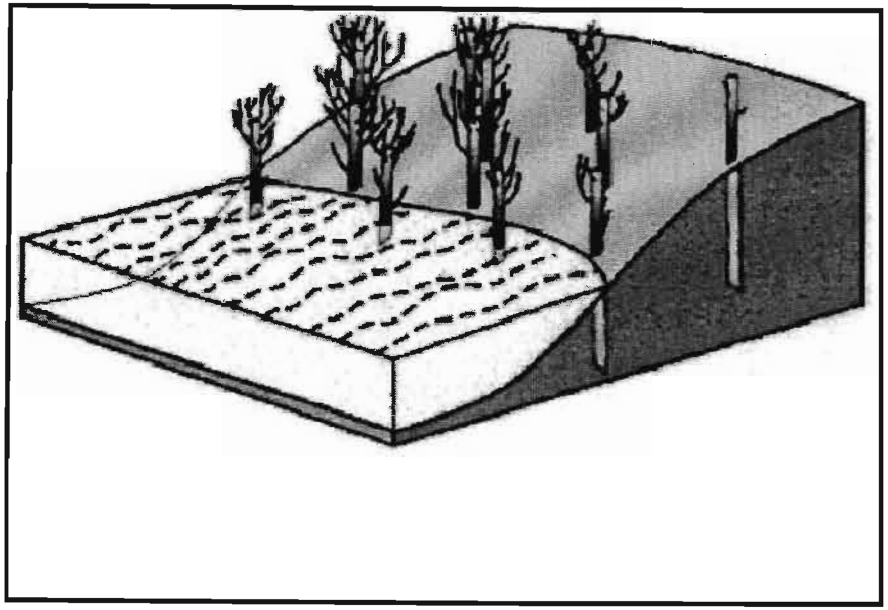
- Will tolerate high boundary shear stress if well anchored
- Should be used with soil bioengineering systems and vegetative plantings to stabilise the upper bank and ensure a regenerative source of streambank vegetation
- Might need eventual replacement if colonisation does not take place or soil bioengineering systems are not used
- Materials may not be available at some locations

Boulders and logs, with root masses attached, placed in and on streambanks to provide streambank erosion mitigation, trap sediment, and improve habitat diversity (FISCRWG, 1998).

For more information, consult:

1. Flosi, G., & F. Reynolds. 1991. *California salmonid stream habitat and restoration manual*. California Department of Fish and Game. USA.
2. U.S. Department of Agriculture, Natural Resources Conservation Service (USDA-NRCS). 1996. Streambank and shoreline protection. In *Engineering Field Handbook*. Part 650, Chapter 16.
3. Vivash, R., & D. Murphy. 1999. *River restoration manual of techniques: Restoring the River Cole and River Skerne, UK* (1st edn.). The River Restoration Centre. UK.

Technique Number 21: Dormant post plantings



Applications and effectiveness

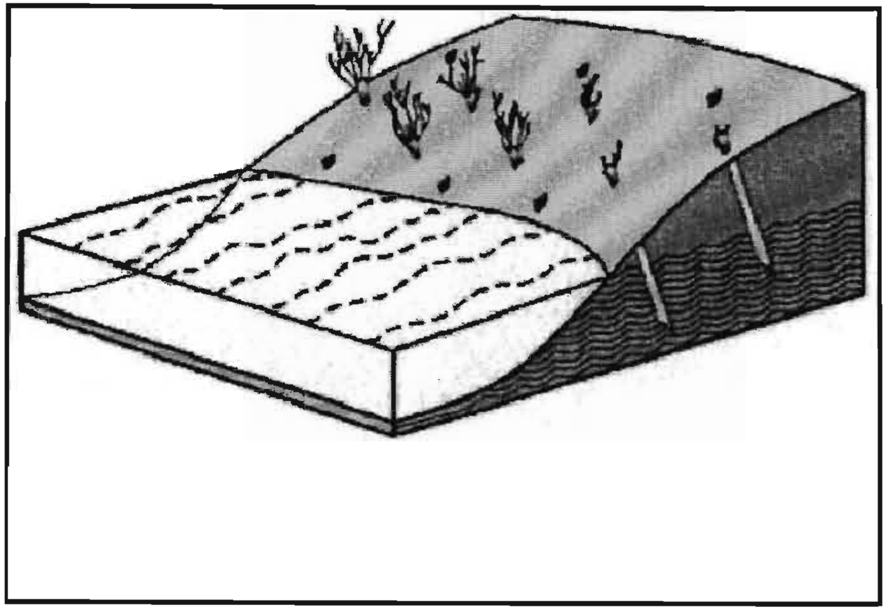
- Can be used as live piling to stabilise rotational failures on streambanks where minor bank sloughing is occurring
- Will reduce near bank stream velocities and cause sediment deposition in treated areas
- Are less likely to be removed by erosion than live stakes or smaller cuttings
- Should, where appropriate, be used with soil bioengineering systems and vegetative plantings to stabilise the upper bank and ensure a regenerative source of stream side vegetation
- Unlike smaller cuttings, post-harvesting may be destructive to the donor stand, therefore, they should be gathered as 'salvage' from sites designated for clearing, or thinned from these dense stands

Plantings of species presented in Table 7, which are embedded vertically into streambanks to increase channel roughness, reduce flow velocities near the slope face, and trap sediment (FISCRWG, 1998).

For more information, consult:

1. Thompson, J.N., & D.L. Green. 1994. *Riparian restoration and streamside erosion control handbook*. Tennessee Department of Environment and Conservation. Tennessee. USA.
2. U.S. Department of Agriculture, Natural Resources Conservation Service (USDA-NRCS). 1995 (unpublished). *Planning and design guidelines for streambank protection*. South National Technical Centre. Texas. USA.
3. U.S. Department of Agriculture, Natural Resources Conservation Service (USDA-NRCS). 1996. Streambank and shoreline protection. In *Engineering Field Handbook*. Part 650, Chapter 16.

Technique Number 22: Live stakes



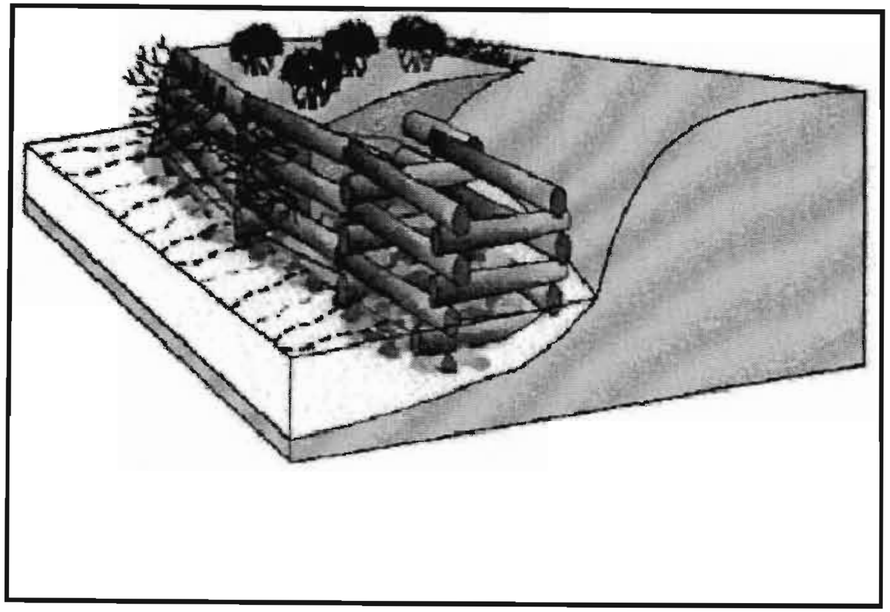
Applications and effectiveness

- Effective where site conditions are uncomplicated, construction time is limited, and a cheap method is needed
- Appropriate for the repair of small earth slips and slumps that are frequently wet
- Requires toe protection where toe scour is anticipated

Live, woody cuttings of species presented in Table 7, which are trampled into the soil to root, growth and create a living root mat that stabilises the soil by reinforcing and binding soil particles together, and by extracting excess soil moisture (FISCRWG, 1998).

For more information, consult:

1. Gray, D.H., & A.T. Leiser. 1982. *Biotechnical Slope Protection and Erosion Control*. van Nostrand Reinhold Co. New York. USA.
2. King County, Washington Department of Public Works. 1993. *Guidelines for bank stabilisation projects*. Seattle. USA.
3. Shields, F.D., & N.M. Aziz. 1992. Knowledge based system for environmental design of stream modifications. *Applied Engineering Agriculture*. ASCE. Vol. 8: 4, 553 - 562.
4. Thompson, J.N., & D.L. Green. 1994. *Riparian restoration and streamside erosion control handbook*. Tennessee Department of Environment and Conservation. Tennessee. USA.



Applications and effectiveness

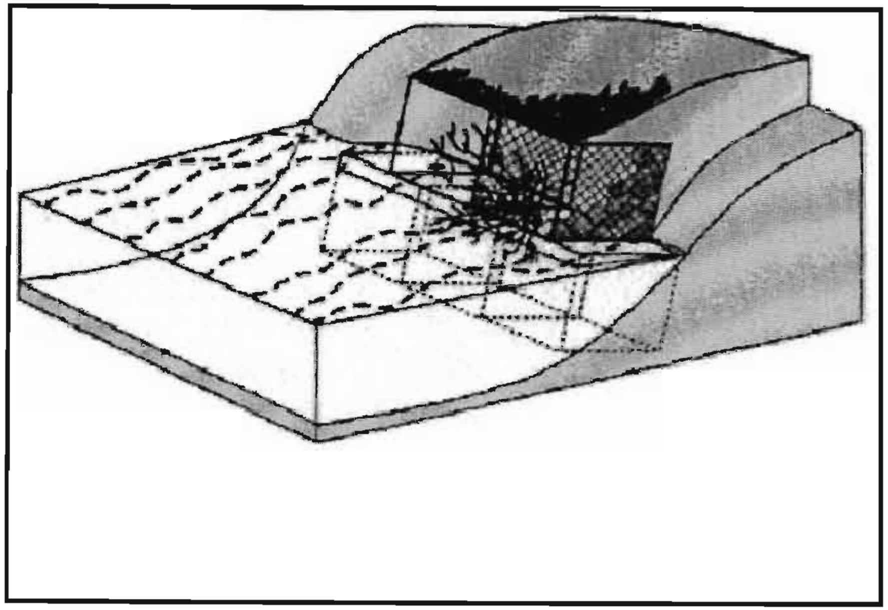
- Provides protection to the streambank in areas with near vertical banks, where bank sloping options are limited
- Furnishes a natural appearance, immediate protection and accelerates the establishment of woody species
- Appropriate on the outside bends, where high velocity is present.
- Appropriate above and below water level where stable streambeds exist
- Don't adjust to toe scour
- Should, where appropriate, be used with soil bioengineering systems and vegetative plantings to stabilise the upper bank and ensure a regenerative source of stream side vegetation

Hollow, box-like interlocking arrangements or untreated log or timber members filled above baseflow with alternate layers of soil material and live branch cuttings that root and gradually take over the structural functions of the wood members (FISCRWG, 1998).

For more information, consult:

1. Flosi, G., & F. Reynolds. 1991. *California salmonid stream habitat and restoration manual.* California Department of Fish and Game. USA.
2. Gray, D.H., & A.T. Leiser. 1982. *Biotechnical Slope Protection and Erosion Control.* Van Nostrand Reinhold Co. New York.
3. King County, Washington Department of Public Works. 1993. *Guidelines for bank stabilisation projects.* Seattle. USA.
4. Shields, F.D., & N.M. Aziz. 1992. Knowledge based system for environmental design of stream modifications. *Applied Engineering Agriculture.* ASCE. Vol. 8: 4, 553 - 562.

Technique Number 24: Vegetated gabions



Applications and effectiveness

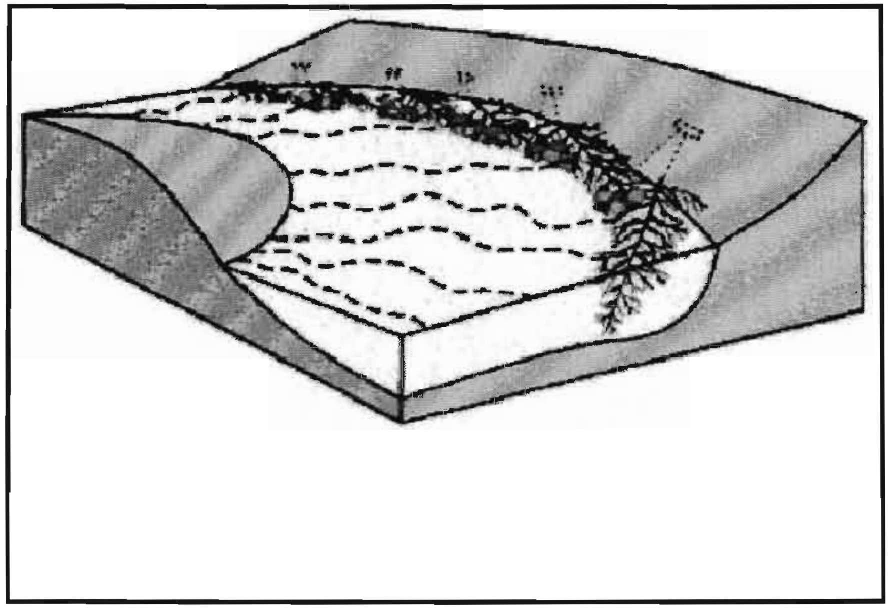
- Useful for protecting steep slopes where scouring or undercutting is occurring or there are heavy loading conditions
- May be a cost effective alternative to other structural solutions where materials are not available
- Appropriate where bank slope is steep and requires structural support
- Requires stable foundation
- Should, where appropriate, be used with soil bioengineering systems and vegetative plantings to stabilise the upper bank and ensure a regenerative source of stream side vegetation

Wire-mesh, rectangular baskets filled with small to medium sized rock and soil and laced together to form a structural toe or sidewall. Live branch cuttings (from table 7) Are placed on each consecutive layer between the rock filled baskets to take root, consolidate the structure, and bind it to the slope (FISCRWG, 1998).

For more information, consult:

1. Flosi, G., & F. Reynolds. 1991. *California salmonid stream habitat and restoration manual*. California Department of Fish and Game.
2. Henderson, J.E. 1986. Environmental designs for streambank protection projects. *Water Resources Bulletin*. Vol. 22: 4, 549 - 558.
3. Shields, F.D., & N.M. Aziz. 1992. Knowledge based system for environmental design of stream modifications. *Applied Engineering Agriculture*. ASCE. Vol. 8: 4, 553 - 562.
4. U.S. Department of Agriculture, Natural Resources Conservation Service (USDA-NRCS). 1996. Streambank and shoreline protection. In *Engineering Field Handbook*. Part 650, Chapter 16.

Technique Number 25: Tree revetments



Applications and effectiveness

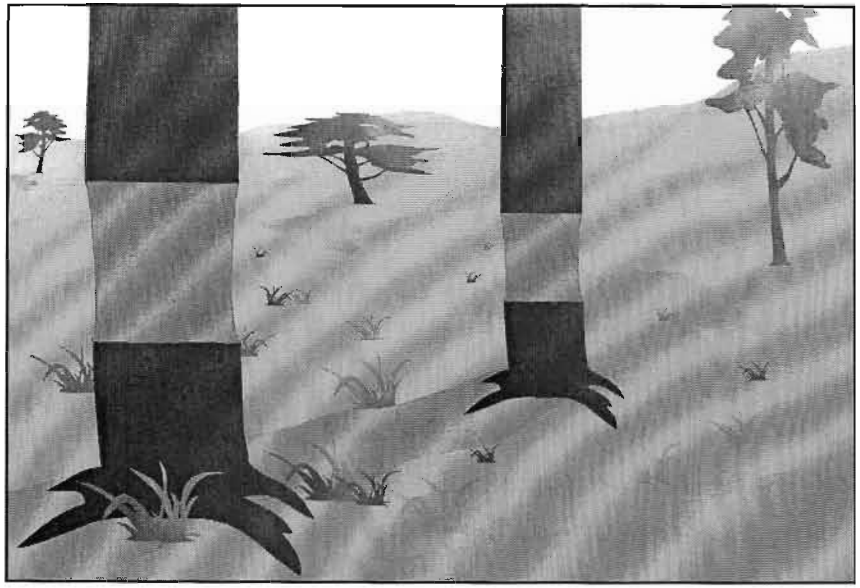
- Design of adequate anchoring system is necessary
- Wire anchoring systems can present safety hazards
- Uses inexpensive, readily available materials
- Has a limited life and may need to be replaced
- Not appropriate for use upstream of bridges or other channel constrictions in case of dislodging and causing damages
- Should not be used if they occupy more than 15% of the channel's cross-sectional area at bankfull level
- Species most resistant to decay are the safest option
- May require toe protection where toe scour is anticipated

A row of interconnected trees (recommended species may be chosen from Table 7) attached to the toe of the streambank or to deadmen in the streambank to reduce flow velocities along eroding streambanks, trap sediment, and provide a substrate for plant establishment and erosion control (FISCRWG, 1998).

For more information, consult:

1. Flosi, G., & F. Reynolds. 1991. *California salmonid stream habitat and restoration manual*. California Department of Fish and Game.
2. King County, Washington Department of Public Works. 1993. *Guidelines for bank stabilisation projects*. Seattle. USA.
3. Shields, F.D., & N.M. Aziz. 1992. Knowledge based system for environmental design of stream modifications. *Applied Engineering Agriculture*. ASCE. Vol. 8: 4, 553 - 562.
4. Shields, F.D. 1983. Design of habitat structures in open channels. *Journal of Water Resources Planning and Management*. ASCE. Vol.109:4.

Technique Number 26: Ringbarking or stem application of herbicides



Applications and effectiveness

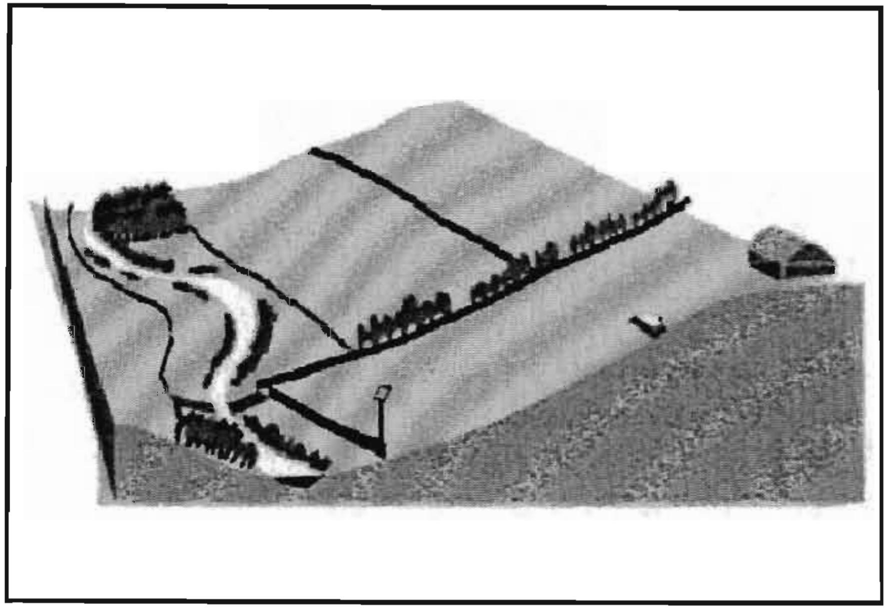
- Cost effective means of eliminating unwanted vegetation
- Will allow for a gradual elimination of plants
- Usually applied when immediate removal of plants is not desirable

Eliminates unwanted trees without immediately reducing their contributions to bank stability.

For more information, consult:

1. Campbell, P. 2000. *Wattle control.* Plant Protection Research Institute. Pretoria. South Africa.

Technique Number 27: Evaluate vegetation



Application

- Inspect the site and determine if any of the structural components (over storey, under storey, ground cover, marginal cover) are missing or are in poor condition
- Note the dominant species in each of the structural components
- Compare this site with the closest site that is thought to be in pristine condition
- Note the species at the reference site and interrogate the database provided (Table 7) to obtain a species list suitable for the site and location
- Encourage the growth of these species at the site by utilising the recommended techniques

To gain an in-depth understanding of the state of the vegetation presently growing on the site. This opportunity will allow the user to come to terms with the vegetation and determine what is lacking. Note, the ultimate required state of vegetation is one which is complete as described in Chapter 2.

For more information, consult:

1. LWRRDC. 1999. *Riparian Land Management Technical Guidelines*. Land and Water Resources Research and Development Corporation. Canberra. Australia. Vol. 1.

6. LWRRDC. 1999. *Riparian land management technical guidelines. On-ground management tools and techniques*. Land and Water Resources Research and Development Corporation. Canberra. Australia. Vol. 2.

Glossary of terms

Aggradation: the building upwards of the streambank by the accumulation of material deposited by water.

Aggregate: cluster of soil particles that adhere to each other and consequently behave as a single mass.

Agricultura; pollution: The liquid and solid wastes from farming, including runoff and leaching of pesticides and fertilisers; erosion and dust from ploughing; animal manure and carcasses; and crop residues and debris.

Algae: Simple rootless plants that grow in sunlit waters in relative proportion to the amounts of nutrients available. They can affect water quality adversely by lowering the dissolved oxygen in the water. Algae are food for fish and small aquatic animals.

Anastomosing channel: a channel that irregularly splits and rejoins.

Autogenic: a process operating within the system.

Bank toe: bottom of the bank.

Bank stability: is defined as the 'natural' rate of bank erosion. This does not imply absolute stability, but the rate of change that may have existed before European settlement. Thus, an unstable bank is a bank that is eroding at a faster rate than natural. You may be able to determine what the natural rate is by comparing the target bank with a nearby reach in near-natural condition.

Bank toe: is the junction of the bank with the bed of the channel. The bank toe is usually marked by a break in slope but often the transition from bank to bed is gradual and the toe is difficult to determine.

Note: This glossary is based largely on the glossary provided by LWRRDC (1999b) and USEPA 1989.

Bank height: is a measure of near bank channel depth measured vertically between the bank toe and bank crest. This will often be the local maximum depth of the channel and is likely to vary from bend to bend.

Basal area: part of the bed or lower bank that surrounds the toe of the bank.

Basal scour: erosion of the base of a streambank by the shear stress of flow.

Brackish water: a mixture of fresh and salt water.

Buffer strip: a vegetated strip of land that functions to absorb sediment and nutrients.

Cantilever failure: undercutting leaves a block of unsupported material on the bank top, which then falls or slides into the stream. A type of mass failure.

Channel avulsion: occurs when there is an abrupt change in stream course and consequent abandonment of the pre-existing channel.

Channel width: is measured from crest to crest.

Channelisation: topography forcing the runoff flow to converge in the hollows or by large objects such as fallen trees.

Critical Bank height: height at which the bank can no longer support itself and fails structurally.

Degraded site: defined as a length of bank which is degraded as a result of a particular process or a combination thereof, bordered on either side by areas where the degrading process(es) change or cease.

De-snagging: removal of snags.

Desiccation: drying and cracking of the bank materials causing it to erode more easily.

Detritus:	organic debris from decomposing organisms and their products. This forms a major source of nutrients and energy for some aquatic food webs.
Ecology:	the relationship of living things to one another and their environment, or the study of such relationships.
Ecosystem:	the interacting system of a biological community and its nonliving environmental surroundings.
Ecotone:	the transition between two or more diverse communities, for example, forest and grassland.
Entrained sediment:	sediment that has been incorporated into a flow by rain splash and flow processes.
Environment:	the sum of all external conditions affecting the life, development, and survival of an organism.
Erosion rate:	is the rate at which the bank face moves (metres/year). This will be an average rate over at least 20 years so that the bank will have been subjected to some major floods. The erosion rate should be determined by existing evidence (e.g. aerial photographs) but can be estimated as a percentage of channel width per year.
Eutrophication:	an increase in the nutrient status of a body of water, which occurs naturally with increasing age of a waterbody, but much more rapidly as a by-product of human activity.
Filter strip:	see buffer strip.
Fluvial:	pertains to water flow and rivers.
Frost heave:	in cold climates, bank moisture temperatures fluctuate around freezing, promoting the growth of ice crystals that dislodge bank materials.

Good vegetation: is a contiguous stand of mature riparian forest established at least the recommended minimum width for its location (i.e. 5m plus the height of the bank).

Headcut: sharp step or small waterfall at the head of a stream.

Isotopic signatures: naturally occurring ratios of stable isotopes in plant or animal tissue. (Isotopes are atoms of the same element with the same chemical properties, but differ in mass).

Macrophytes: large vascular plants.

Marginal cover: species of sedges rushes and reeds which grow on the margins of the average water level.

Mass failure: a form of bank erosion caused by blocks of material sliding or toppling into the water.

Microtopography: variations in the topography of the ground surface at the scale of centimetres to metres.

Moderate vegetation: is a riparian forest that is not contiguous (compared to natural remnants or other local expert advice), is immature (perhaps a recent plantation), or does not meet the recommended minimum width requirement (i.e. 5m plus the height of the bank).

Overburden: burial by deposited sediment.

Plantation maturity: is defined as the time it takes the vegetation to have a major influence on the erosion rate (e.g. to a closed canopy). Plantations in the wet-tropics can mature within ten years but this could be up to 50 years in drier areas.

Poor vegetation: lacks one or more structural elements (Over storey, under storey, ground cover, or marginal cover), is in a generally degraded condition, is less than the recommended width for its location, and performs no stabilising role.

Rain splash: the dislodgement of sediment by rain which travels down the bank and into the flow.

Rill erosion: small, often short-lived, channels that form in cropland and unsealed roads after intense rains.

Riparian area: any land which adjoins, directly influences, or is influenced by a body of water and includes land which:

- is immediately alongside small creeks and rivers, including the river bank itself;
- is a temporary surface-water conveyor such as a gully;
- surrounds lakes;
- interacts with the river in times of flood;
- holds water, such as a wetland.

Riparian zone width: is the minimum width of riparian forest required for ongoing bank stability. It is measured from the bank crest away from the channel. The minimum width of the riparian zone varies with bank height and bank erosion rate.

Riprap: a blanket of stones extending from the toe of the slope to a height which extends over the degradation and protects it from the force of the flow.

Rock revetment: a structure which provides armour for the stream bank against fluvial erosion, as well as providing stabilisation against slumping.

Rock/pile groyne: structures (usually impermeable) that project from the stream bank. They are designed to increase flow resistance and direct stream flow away from the bank through a preferred channel alignment.

Rotational failure: a form of bank erosion caused by a slip along a curved surface that usually passes above the toe of the bank.

Scour: a form of bank erosion caused by sediment being removed from the stream banks particle by particle. Scour occurs when the force applied to a bank by flowing water exceeds the resistance of the bank surface to withstand those forces.

Sedimentation:	The settling of solids out of water by gravity.
Sediments:	Soil, sand, and minerals washed from land into water, usually after rain. Sediments pile up reservoirs, rivers, and harbours, destroying fish-nesting areas and holes of water animals and clouding the water so that needed sunlight may not reach aquatic plants. Careless farming, mining and building activities will expose sediment materials, allowing them to be washed off the land after rainfalls.
Shear force:	the force per unit area exerted by water as it shears over a surface.
Sheet erosion:	erosion on hillslopes by dispersed overland flow.
Silt:	fine particles of sand or rock that can be picked up by the air or water and deposited as sediment.
Slab failure:	a type of mass failure caused by a block of soil toppling forward into the channel.
Slumping:	the mass failure of part of the streambank.
Snags:	large woody debris such as logs and branches that fall into rivers.
Stratigraphy:	the sequence of deposited layers of sediment.
Stream order:	classification of streams according to their position in the stream network, for example, a first order stream has no tributaries. Streams become larger as their order rises and an increasing number of segments contribute to the flow.
Sub-aerial erosion:	erosion caused by exposure of streambank to air.
Succession:	directional or continuous pattern of colonisation and extinction of a site by populations of plants and/or animals.
Surcharge:	the weight imposed on a bank by vegetation.

Surface water: All water naturally open to the atmosphere (rivers lakes reservoirs, streams, impoundments, seas, estuaries etc.); also refers to springs, wells or other collectors that are directly influenced by surface water.

Tensile stress: the force per unit area acting to pull a mass of soil or tree root apart.

Toe scour: see basal scour.

Toe: See bank toe.

Urban runoff: Stormwater from city streets and adjacent domestic or commercial properties that may carry pollutants of various kinds into receiving waters.

Water pollution: The presence in water of enough harmful or objectionable material to damage water quality.

Wetlands: An area that is regularly saturated by surface water or groundwater and is subsequently characterised by a prevalence of vegetation adapted for life in saturated soil conditions. Examples include swamps, marshes and estuaries.

Windthrow: shallow rooted, stream-side trees blow over, delivering bank sediment into the stream.