A DECISION SUPPORT SYSTEM FOR REHABILITATION AND MANAGEMENT OF RIPARIAN SYSTEMS
K5/1064

Report to the
Water Research Commission

Prepared by

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EXECUTIVE SUMMARY

The field of river rehabilitation or restoration has experienced considerable growth in the last decade, particularly in Europe, the United States of America and in Australia. In contrast, while there is a growing research interest in river rehabilitation in South Africa, very few significant rehabilitation projects have been undertaken and there is a lack of guidelines specific to South Africa. One of the significant areas of progress in Australia has been the development of a framework for planning rehabilitation projects. This framework was adopted, with slight modification, as the basis for river rehabilitation planning in the project and specific research projects were undertaken to develop components of a decision support system to assist in the planning and implementation of rehabilitation projects.

This research project represents an initial level of investigation aimed at developing a set of tools and approaches that would have general applicability for river rehabilitation in South Africa. They have been developed principally for application in agricultural landscapes, and for streams of third order or less. Achievements of the project are reported with reference to the stated project objectives below:

(i) *Formulation of a procedure which identifies and prioritises sites of intervention and promotes cost-effective rehabilitation of land and riparian systems, and integration of this procedure with the linkages identified in (iv) below*

A planning framework and process for river rehabilitation in South Africa was adapted from work done in Australia, as well as on the basis of experience elsewhere in the world. The following techniques, protocols and methods (decision support systems) developed by the project fit sequentially into this framework:

- An approach for mapping landscape scale assets
- A methodology for identifying and mapping wetland boundaries from satellite imagery, as well as a new field-based approach to be used in conjunction with the current wetlands delineation procedures
- A technique for identifying and mapping riparian, stream bank and in-channel assets and problems at the scale of a river reach
- A GIS based protocol for identifying priority river reaches for rehabilitation and buffer establishment for sediment control, particularly relevant to the sugar and forestry industries
- A protocol for assessing the nitrate attenuation potential of riparian zones, as well as a protocol for sizing riparian buffers to achieve an approximately 65% reduction in nitrates, particularly relevant to commercial agriculture
- A prototype decision support system for selecting appropriate techniques for:
    - streambank rehabilitation
    - riparian zone rehabilitation
- A database of appropriate plant species for rehabilitation in South Africa

(ii) *Evaluation of the application and transferability of the procedure to other river systems*

A specific criterion in the development of the above protocols and decision support systems was to make the approach as broadly applicable as possible. The work leading up to these protocols and methods was tested in a number of areas in KwaZulu-Natal including the Mhlathuze catchment, Maputaland, Natal Midlands, the Drakensberg. While some aspects of the project have focussed on a catchment in the Western Cape, the principal area of application and testing has been KwaZulu-Natal.

However it should be stressed that there is the expectation that the approaches developed will be applicable throughout South Africa, although a full testing and evaluation of all aspects was beyond the scope of this phase of the project. This has emerged as a key recommendation for further research.

(iii) *Development and enhancement of capacity in rehabilitation and river management amongst previously disadvantaged groups*

Development and enhancement of capacity in river rehabilitation and management has been achieved through the following means:

- Inclusion of the approach, protocols and decision support systems as a 3-day module within the Integrated Catchment Management elective in the CEAD Masters Programme in 2000 and 2001. This resulted in 15 students being trained in the fundamental principles of river rehabilitation, 3 of which came from previously disadvantaged backgrounds.

- Ten of these students received further mentoring and training as they elected to undertake their dissertation research within the framework of this WRC Project. Four of these students came from previously disadvantaged backgrounds. Four of the eight students who graduated with masters degrees received distinctions for their research products.

- The training course in river rehabilitation in 2002 resulted in a further 20 people being trained, 6 of which came from previously disadvantaged backgrounds.

(iv) *Establishment of effective conceptual and operational linkages between the Land Care initiative of the Department of Agriculture (Directorate of Resource Conservation), management of rivers (Department of Water Affairs and Forestry; River Health Programme, Working for Water Campaign, Ecological Reserve determination initiatives) and other research initiatives (e.g. WRC funded project on DSS development in the Mhlathuze catchment, various initiatives at the Centre for Water in the Environment, University of the Witwatersrand)*

- Conceptual links have been established with the Resource Directed Measures approaches to the determination of the Reserve, and the River Health Programme. Opportunities for the implementation of the products developed have been identified within the Working for Water programme and the Landcare programme. However operational linkages are not well established yet as these are seen to be linked to a future testing phase of the project.

The various papers presented in the appendices of this report provide a full description of the various methods, protocols and decision support systems. For further detail the six masters dissertations may be consulted. The six appendices provide specific recommendations for further research, development and testing. However two over-arching recommendations are summarised here:

(i) Catchment-scale implementation, testing and refinement

The principal recommendation emerging from this research is that the techniques and protocols should be tested in a relatively small catchment (<300km^2) and through implementation of the rehabilitation planning framework with stakeholders in the catchment. Undertaking this exercise on a catchment basis with an emphasis on establishing priorities for action will provide a rigorous basis for evaluating the utility of the techniques and protocols and will assist in identifying further development needs. Such an exercise could form a sound basis for the development of a catchment management plan.

(ii) Establishment of regional (provincial) centres of expertise

This research project has resulted in the accumulation of a considerable set of resources on river rehabilitation and management. The project has also generated a fair amount of expertise and a number of developing techniques and protocols. Establishing regional centres of expertise would provide a node for the continued development of the discipline and also a resource for stakeholders to access.

ACKNOWLEDGEMENTS

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Chapter 1: INTRODUCTION

Degradation of wetland, river and riparian habitats environments in South Africa has been raised as a major concern, and there is an acknowledged need to implement management strategies to halt this trend. New legislation, such as the National Water Act which provides for ecological flow requirements and supports catchment management through the establishment of appropriate institutional structures are important steps in this regard. However, a number of other initiatives have also recently been launched which address aspects of catchment rehabilitation and management (e.g. LandCare Initiative, Working for Water Campaign).

Functioning riparian areas perform vital hydrological and ecological services, and the management and rehabilitation of these areas is a critical aspect of catchment management. It is important that the links between land use and river systems are firmly established so that ‘land care’ and ‘water care’ are seen to be inseparable parts of sustainable living. The project was therefore motivated on the grounds of :

- the need for catchment rehabilitation and a process (land care) to achieve this
- the need for rehabilitation of riparian systems and a process to achieve this
- the need for information, knowledge and capacity to promote and link the land care and catchment management initiatives of the Departments of Agriculture and Water Affairs and Forestry, as well as many other initiatives.

Rehabilitation of streams, rivers, wetlands and riparian areas is rapidly becoming a worldwide phenomenon. Many countries, including the United States of America, Australia, the United Kingdom and other countries in Europe, have produced technical guidelines for river rehabilitation. However, in South Africa little effort has been directed towards river rehabilitation and there are few local examples. While guidelines from other parts of the world are available, the extent to which these are applicable to South African conditions is not known.

This research project represents an initial level of investigation aimed at developing a set of tools and approaches that would have general applicability for river rehabilitation in South Africa. They have been developed principally for application in agricultural landscapes, and for streams of third order or less. The work leading up to these protocols and methods was tested in a number of areas in KwaZulu-Natal including the Mhlathuze catchment, Maputaland, Natal Midlands, the Drakensberg. Thus, while some aspects of the project have focussed on a catchment in the Western Cape, the principal area of application and testing has been KwaZulu-Natal.

This report is intended as a brief overview of the research undertaken during this research project. Additional detail is provided in the form of the six papers in the appendices, and the eight masters dissertations available from the University of Natal, Pietermaritzburg.

Chapter 2 : AIMS AND OBJECTIVES

2.1 Introduction

The primary aim of this project was the development of a decision support system for the rehabilitation and management of riparian areas. The stated objectives of the original project proposal are as follows:

(i) Formulation of a procedure which identifies and prioritises sites of intervention and promotes cost-effective rehabilitation of land and riparian systems, and integration of this procedure with the linkages identified in (iv) below

(ii) Evaluation of the application and transferability of the procedure to other river systems

(iii) Development and enhancement of capacity in rehabilitation and river management amongst previously disadvantaged groups

(iv) Establishment of effective conceptual and operational linkages between the Land Care initiative of the Department of Agriculture (Directorate of Resource Conservation), management of rivers (Department of Water Affairs and Forestry; River Health Programme, Working for Water Campaign, Ecological Reserve determination initiatives) and other research initiatives (e.g. WRC funded project on DSS development in the Mhlathuze catchment, various initiatives at the Centre for Water in the Environment, University of the Witwatersrand)

2.2 Definitions and key principles

2.2.1 Definitions

Even a cursory examination of the literature reveals that authors use a variety of terms to describe the process of improving some aspect of river ecosystem structure or functioning, most typically the terms *rehabilitation* or *restoration*. Whilst these terms are sometimes used interchangeably, more often they imply a specific intent or purpose.

(i) Restoration

The Federal Inter-agency Working Group on Stream Restoration (FISRWG 1998) define ecological restoration as '*the process of returning an ecosystem as closely as possible to predisturbance conditions and functions*'. They stress that it is implicit in this definition that stream ecosystems are dynamic and that it is consequently not possible to recreate a system exactly. Rather, the stream restoration process is aimed at reestablishing the '*general structure, function and dynamic, but self-sustaining behaviour of the ecosystem*' (FISRWG 1998). As Rutherfurd, Jerie and Marsh (2000) have stated it, ideal restoration would typically involve the sequential achievement of the following objectives:

(a) restore the natural range of water quality
(b) restore the natural sediment and flow regime (seasonal, annual and decadal fluctuations)
(c) restore the natural channel geometry and stability
(d) restore the natural riparian plant community
(e) restore indigenous aquatic plants and animals if they do not colonise on their own

(ii) Rehabilitation

In its most simple form, rehabilitation can be considered as a series of actions which make the landscape useful again after a disturbance, and usually involves '*the recovery of ecosystem functions and processes in a degraded habitat*' (Dunster & Dunster 1996). The Federal Inter-agency Working Group on Stream Restoration consider the most important distinction between restoration and rehabilitation to be the fact that whilst the former implies a return to pre-disturbance conditions, the latter does not. The purpose of rehabilitation is to establish geomorphological and hydrological landscape '*that support the natural ecosystem mosaic*'.

(iii) Reclamation and remediation

Reclamation is viewed as a far more utilitarian endeavour, typically a series of actions where the intention is to change the biophysical capacity of the system, and which results in an ecosystem which is different from the one prior to reclamation (Dunster & Dunster 1996). This implies adapting an ecosystem to suit a specific human purpose, which may or may not be consistent with its ecological functioning. Remediation is defined by Rutherfurd, Jerie and Marsh (2000) as actions aimed to establish a new ecosystem on the basis that the stream has changed so much from the original condition that it is no longer relevant, and that therefore a new condition is intended.

The National Research Council (1992) considers restoration to differ '*from rehabilitation and reclamation in that restoration is a holistic process not achieved through the isolated manipulation of individual elements. While restoration aims to return an ecosystem to a former natural condition, rehabilitation and reclamation imply putting a landscape to a new or altered use to serve a particular human purpose*.' This is somewhat different to the view of Rutherfurd, Jerie and Marsh (2000) who see rehabilitation as a trajectory towards restoration, but which may not necessarily involve complete reinstatement of all structure and functions (Figure 2.1). Their argument for utilising the term rehabilitation as opposed to restoration, rests on the fact that in many cases it is difficult to determine what the pre-disturbance condition of the river was. Secondly, restoration necessarily requires modification of the physical and biological character of the reach to re-create the original state, including modification of all the inputs including, fluctuations in flow and quality of flow as well as sediment inputs and biota. These authors further state that this would probably only be possible if the whole river network, and possibly much of the catchment was also restored. In Australia, and most certainly in South Africa, this is an unlikely scenario.

In this document the term rehabilitation will be used. This is for both the reasons cited by Rutherfurd, Jerie and Marsh (1999) and the fact that a particular group of stakeholders may wish to achieve a specific purpose in implementing rehabilitation measures, and which may not have been a component of the pre-disturbance state. This does not necessarily imply subjugation of ecological processes, but rather that priority may be given to the enhancement of a particular ecosystem service. This is a more utilitarian view than that of the Federal Inter-agency Working Group on Stream Restoration, but it should be stressed that at all times the focus of rehabilitation will be the re-establishment of an appropriate ecosystem structure and functioning, which must be self-sustaining.

In some cases there may be few options for rehabilitation, and the only possible action may be to attempt to stop further degradation of the system. In this case it may only possible to *stabilise* a component of the system. This in turn may or may not result in regeneration of some ecosystem processes. For example, this would be the case where it may be necessary to stabilise a stream bank to prevent erosion and loss of property. Often this does not constitute rehabilitation as the causes of the problem have not been addressed and the action may well have simply moved the problem further downstream.

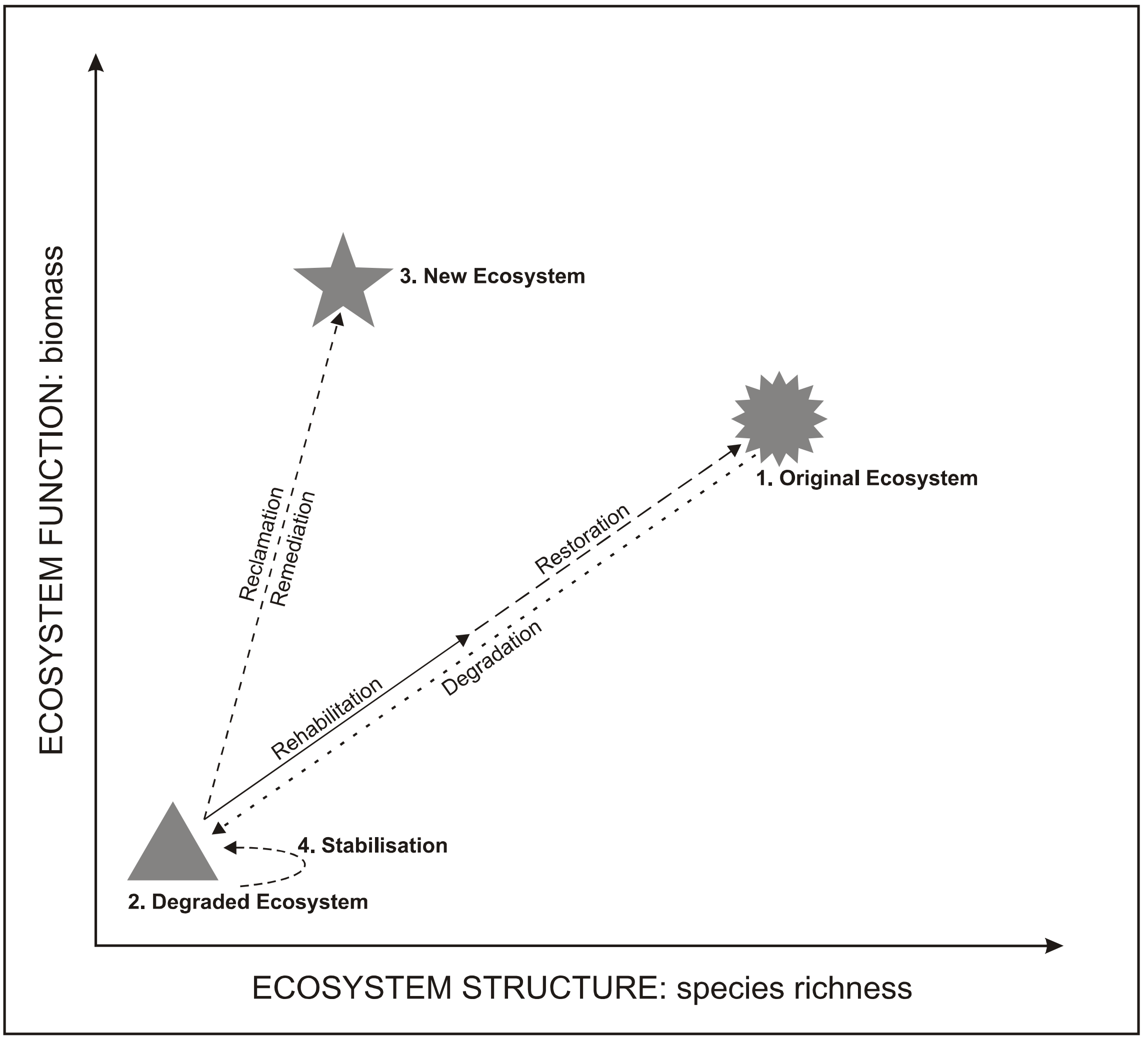

Figure 2.1 : Differences between restoration, remediation /reclamation, rehabilitation and stabilisation (*after* Rutherfurd, Jerie & Marsh 1999). **Restoration** means returning all aspects to the pre-disturbance level of structure and functioning. **Rehabilitation** refers to actions which reinstate some of the original ecosystem processes and structure, but with the intention of making it as close as possible to the natural condition. **Remediation** or **reclamation** implies the creation of a new ecosystem, with a different structure and functioning. This could be because rehabilitation is not possible, or because a different ecosystem state is desired by stakeholders. **Stabilisation** means the halt, or at least at reduction in the rate of degradation through a specific action. However, in many cases this means moving the consequences further downstream.

2.2.2 Key principles

During the course of the project a number of key principles were adopted in discussion with the Steering Committee. As these principles and decisions of the Steering Committee are fundamental to the application and transferability of the products of this research project, they are highlighted below:

- Riparian systems were defined as being streams and drainage lines comprising in-channel, stream bank and riparian zone habitats. Wetlands are explicitly included as part of riparian systems. The approach of the project has been to focus on the goods and services provided by riparian systems, and that the purpose of rehabilitation is to improve or restore as many of the ecosystem functions of these systems as possible.

- A decision support system (DSS) was considered to be any suite of techniques or individual protocols which could be used in succession or in parallel to assist in the planning and management of river rehabilitation. An integrated or streamlined DSS could be an ultimate product but was not considered an essential final product of this research.

- The scale of application of the decision support systems developed in this project is at the local scale, principally first, second and third order streams. Importantly, in respect of objective (iv) above, this is at a significantly lower stream order than the current focus of initiatives such as the River Health Programme and Resource Directed Measures for aquatic ecosystems.

- Whilst the Mhlathuze Catchment was originally identified as the pilot area, it become necessary to broaden the geographic area for developing and testing of the decision support systems to make best use of opportunities for synergy with other initiatives. As a consequence some research was been undertaken in the Western Cape (Rondegat River), as well as in the Midlands, Zululand and also within Pietermaritzburg.

- An important aspect raised at an early stage in the project was the need for a framework in which river rehabilitation can be conceptualised and planned. During the initial stages of the project, various approaches to river rehabilitation and planning were reviewed and considered for possible application in South Africa. The Australian model (Rutherfurd, Jerie & Marsh 1999) was adopted as the framework for integrating various components of the decision support systems developed in this research programme (Figure 2.1).

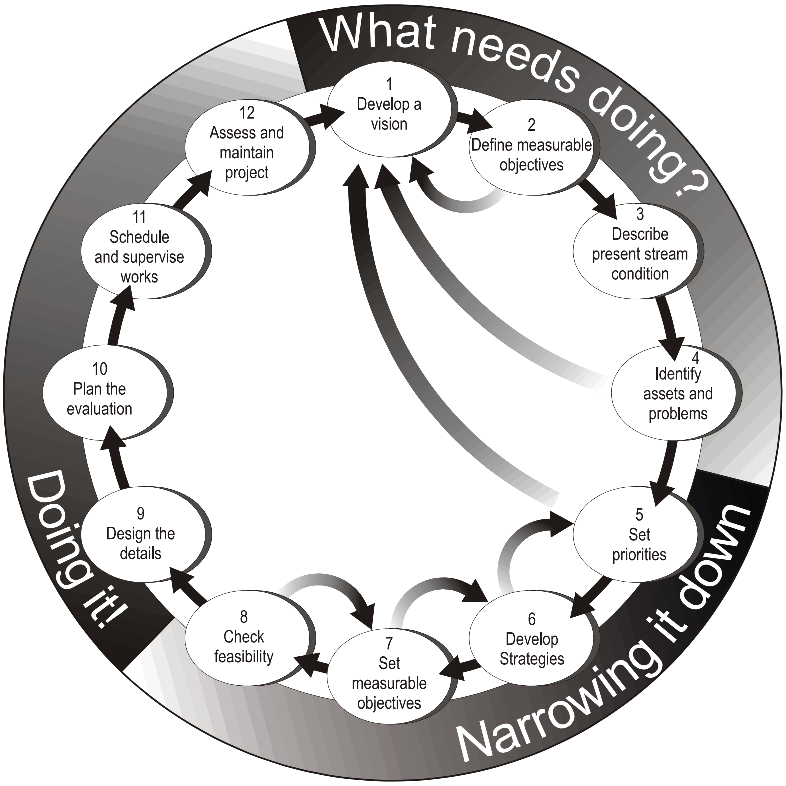

Figure 2. 1: A proposed framework for river rehabilitation in South Africa (*after* Rutherfurd, Jerie & Marsh 1999)

- The planning framework provides a system for taking an intervention from the conceptualisation stage right through to the implementation phase. As the objectives of this research project did not provide for the implementation of any rehabilitation projects, the focus of the DSS components is necessarily on the earlier phases of the framework (Steps 1: *Setting the Vision* to Step 6: *Develop strategies*).

Chapter 3: RESEARCH APPROACH AND CAPACITY BUILDING

3.1 Research approach

The principal mechanism for achieving the project aims (which included capacity building) was the utilisation of post-graduate students at the Centre for Environment and Development. The individual projects were principally conceptualised as research projects which would meet the requirements for the Master of Environment and Development (MEnvDev) mini-dissertation, although one research project was for the degree of Master of Science, and another for a Master of Social Sciences. Each of the individual research projects were selected to provide a specific input into the rehabilitation planning framework. Table 3.1 overleaf provides an overview of the rehabilitation planning framework steps in relation to the individual research projects, showing the research degree, student, supervisor, and completion status. One difficulty that such an approach raises is the significant volume of thesis-based research that is generated. Review of the eight mini-dissertations and one MSc was considered to be beyond the terms of reference of the Steering Committee due to the time that such an undertaking will require. The approach that was adopted was that internal and external examiners of these dissertations would provide a measure of scientific review and that the role of the Steering Committee was on evaluation of the approach with respect to overall project objectives and technology transfer.

Each of the case studies was also selected to develop approaches for a variety of land-uses, stakeholders and specific riparian zone functions. The transferability of approaches developed in each case study however, was an integral part of the research project. In the initial phase three key riparian zone functions were selected for further research, namely; habitat provision, sediment trapping, and nutrient assimilation (mainly nitrate). Table 3.2 provides an indication of the applicability of the approaches developed within each case study to other land-uses, the location of the particular case study, and the extent to which the approaches developed in each case study contribute to each of the rehabilitation framework planning steps.

Table 3.1: Individual research projects and their status in relation to the river rehabilitation planning framework

REHABILITATION PLANNING FRAMEWORK STEP	PROJECT	DEGREE, STUDENT AND SUPERVISOR(s)	STATUS
Step 1: Develop a vision	**Project A: Riparian rehabilitation and land use in a wilderness area: A case study of perceptions needs and management actions**	**Rodney February MEnvDev (NW Quinn, D Versveld)**	**COMPLETE**
	Project B: Riparian management and resource utilisation in a rural community	**Cleophas Mudzinga (NW Quinn)**	**WITHDRAWN**
Step 2: Define measurable objectives	**No specific project was identified for this step as the approaches defined by Rutherfurd, Jerie & Marsh (2000) are considered to be adequate for South African purposes. However, the more structured approach of Rogers & Bestbier (1997) are worthy of testing in this context, and may represent a useful approach to implementing Steps 1 and 2.**		
Step 3: Describe present riparian condition	**Project C : Assessing riparian habitat: An approach for planning rehabilitation**	**Duncan Challen MEnvDev (NW Quinn, T Everson)**	**COMPLETE *with distinction***
	Project D : Improved techniques for mapping wetlands and riparian zones from satellite imagery	**Dechlan Pillay MEnvDev (F Ahmed)**	**COMPLETE**
	Project E : Mapping wetlands and riparian zones using magnetic susceptibility	**Megan Watson MEnvDev (NW Quinn, J Hughes)**	**COMPLETE**
	Project F : Approaches to biogeographic classification of rivers for rehabilitation planning	**Daniel Sebake MEnvDev (F Ahmed, NW Quinn)**	**INCOMPLETE**
Step 4: Identify assets and problems	**Project C incorporates procedures for identifying assets and problems with respect to riparian zone and in-channel habitats** **Project I below also incorporates procedures for identifying streambank stability problems** **Project G below also incorporates procedures for identifying problems with respect to commercial forestry**		
Step 5: Set priorities	**Project G : Identifying priorities for rehabilitation within commercial plantation forestry**	**Michael Horswell MSc (NW Quinn, T Hill)**	**COMPLETE *with distinction***
	Project H : An economic analysis of the eradication and management of invasive alien vegetation in riparian zones of the Mhlathuze Catchment	**Jennifer Cooper MSocSci (Economics) (J Schroen, NW Quinn)**	**COMPLETE *with distinction***
	Projects C and I include approaches to setting priorities for habitat rehabilitation and bank stability respectively **Project J incorporates procedures for identifying priorities within commercial agriculture where nutrient loading to streams may be a problem**		
Step 6: Develop strategies	**Project I : A prototype decision support system for streambank stabilisation**	**Kilaan Schoeman MEnvDev (NW Quinn, T Everson)**	**COMPLETE *with distinction***
	Project J : The use of riparian buffer zones for the attenuation of nitrate in agricultural landscapes	**Claire Blanché MEnvDev (NW Quinn)**	**COMPLETE**
	Project C includes methods for recommending specific rehabilitation measures within areas of commercial afforestation		

Table 3.2: Matrix showing applicability to landuses, case study locations and contribution to each of the rehabilitation planning steps

PROJECT	APPLICABILITY TO LANDUSE					CASE STUDY LOCATION				CONTRIBUTION TO REHABILITATION PLANNING STEP					
	Forestry	Sugarcane	Agriculture	Urban	Conserve	Mhlathuze	Midlands	Urban	Other	1	2	3	4	5	6
Project A: Riparian rehabilitation and land use in a wilderness area: A case study of perceptions needs and management actions	✓	✓	✓	✓	✓				✓	✓					
Project B: Riparian management and resource utilisation in a rural community			✓							✓					
Project C : Assessing riparian habitat: An approach for planning rehabilitation	✓	✓	✓	✓	✓	✓						✓	✓	✓	
Project D : Improved techniques for mapping wetlands and riparian zones from satellite imagery	✓	✓	✓	✓		✓						✓			
Project E : Mapping wetlands and riparian zones using magnetic susceptibility	✓	✓	✓	✓		✓	✓	✓				✓			
Project F : Approaches to biogeographic classification of rivers for rehabilitation planning	✓	✓	✓	✓	✓		✓					✓	✓	✓	✓
Project G : Identifying priorities for rehabilitation within commercial afforestation	✓	✓	✓			✓							✓	✓	✓
Project H : An economic analysis of the eradication and management of invasive alien vegetation in riparian zones of the Mhlathuze Catchment	✓	✓	✓			✓								✓	
Project I : A prototype decision support system for streambank stabilisation	✓	✓	✓	✓	✓			✓					✓	✓	✓
Project J : The use of riparian buffer zones for the attenuation of nitrate in agricultural landscapes		✓	✓				✓						✓	✓	✓

3.2 Capacity building

3.2.1 Masters degrees

Thus of the ten Masters students, eight have completed their degrees (four with distinction for the research project), and one will submit his dissertation for examination before June 2003. One student did not complete his dissertation and exited with a Diploma. However in this latter case, it should be noted that although the student did not manage to complete research component due to personal reasons, the student did spend six months working on the project and gained valuable experience.

3.2.3 Training course in river rehabilitation

A new Honours level course in River Rehabilitation & Planning was developed and approved by the University of Natal (Table 3.3). This represents the first formal training course in river rehabilitation and planning in Africa. An initial presentation of the course was held from the 27 to 31 May 2002, and led by Dr Nevil Quinn and Professor Susan Marriott. The course was not that widely advertised and yet attracted considerable interest, with many requesting to be notified when it scheduled to be run again. A total of 20 participants attended including representatives from the following categories:

- University of Natal Students (CEAD and Discipline of Geography)
- Umgeni Water
- Msunduzi Catchment Management Forum
- Greater Edendale Environmental Network (GREEN)
- Vuka Environmental Community Project
- Consulting Civil Engineer (JHB)
- Mondi Wetlands Project
- Umlaas Irrigation Board
- Western Cape Nature Conservation
- Council for Geosciences

Six of the participants represented individuals from a previously disadvantaged background. The course will be run on an annual basis over a week between March and June each year. The course will be open to all who have an interest in river rehabilitation and will be advertised nationally.

The course materials which have been developed are also available to any other centres which may wish to develop a course of their own. The course has been structured using problem-based learning principles.

Table 3.3: Outline of a course in River Rehabilitation and Planning

Template for the Internal Approval of modules at the University of Natal

Title of Module	River Rehabilitation and Planning
Module Code	EDEL716
NQF Level	7b
Credit value of the module	4
Discipline	Centre for Environment and Development
School offering the module	Applied Environmental Sciences

1. Programme(s) on which the module will be offered

An elective course for Master of Environment and Development. Any Honours programmes.

Pre-requisites for the module

Admission to the programme in Environment and Development or relevant background acceptable to the Dean

2. Purpose of the module

To provide an introduction to river rehabilitation and planning, focusing on problem identification, priority setting, techniques and intervention as well as monitoring and evaluation.

3. Statement of specific learning outcomes for the module

On completion of this module, learners should be able to:

- identify assets and problems for a river reach or system
- contribute to the setting of a vision, goal and objectives for the river reach/system
- identify priorities for rehabilitation and appropriate techniques for implementation
- prepare a rehabilitation strategy and plan (river action plan)
- prepare a monitoring and evaluation plan

4. List of content topics

River rehabilitation concepts, definitions, principles and philosophy. Conceptual framework for river rehabilitation, planning and management. Approaches to setting objectives, community participation. Techniques for identifying problems and mapping assets. Hydrological and geomorphological principles and techniques. Riparian and in-channel ecosystems and their importance. Rehabilitation techniques and bioengineering. Setting priorities and formulation of a rehabilitation strategy (river action plan). Implementation, monitoring and evaluation. International case studies in river rehabilitation.

5. Types of delivery and estimated notional study hours per type

Student Activity	**Number of notional study hours (For the whole module)**
Lectures	10
Practicals	5
Tutorials	10
Field Trips	5
Placements	
Tests/exams	
Other (specify)	
Sub-total: No. of contact hours	**30**
Resource-based learning	
Self-directed study	
Study on assignments	10
Exam preparation	
Other (specify)	
Sub-total: No. of notional self-study hours	**10**
Total No. of notional study hours required to complete the module	**40**

6. Teaching-learning methods used on the module

Lectures, group work assignments, videos, guided reading, guest presentations

7. Statement of assessment criteria

Learners must demonstrate that they:

- Have a sound understanding of the rehabilitation principles
- Are able to identify river problems and assets
- Are able to identify appropriate interventions and select rehabilitation techniques
- Can prepare a river action plan and are able to review and evaluate their action plans

8. Methods of assessment to be used in the module (indicate the weighting for each method)

Preparation of a river action plan for a reach of river, including all the above components

Chapter 4 : OVERVIEW OF RESEARCH PRODUCTS

4.1 Introduction

This chapter provides an overview of the principal research products developed during this project. For full details of each product, readers are referred to the relevant masters degree. Several of the research products are described in papers provided in the appendices. Each of the products comprises either a protocol or decision support system which has a particular application within the overall planning framework.

4.2 The planning framework

Rutherfurd, Jerie and Marsh (2000) considered a number of approaches to planning rehabilitation initiatives (Newbury & Gaboury 1993; Kapitsky *et al.* 1998) and subsequently devised a 12-step planning procedure (Table 4.1). This has been adopted as the core of the framework suggested for use in South Africa, although with slight modifications. These modification are based primarily on insights derived from the experience of South African researchers in the Kruger National Park Rivers Research Programme.

Table 4.1 : A 12-step approach to river rehabilitation (Rutherfurd, Jerie & Marsh 2000)

STEP	KEY QUESTION	ACTION
1	What are the goals for rehabilitating your stream?	**Develop a vision.** By the end of this step you should have described a broad goal, or 'vision' of what you want your stream to be like when you have finished the rehabilitation. You will need the vision to keep you on track as you develop your rehabilitation plan.
2	Who shares your goals for the stream?	**Share the vision**. Stream rehabilitation is a subset of catchment management. Streams have many roles, not all of which relate to their ecological or environmental values. Do other people share your vision of an ecologically rehabilitated stream?
3	How has your stream changed since European settlement?	**Describe the stream condition**. Describe the pre-disturbance stream as well as its present condition
4	What are your streams natural assets?	**Identify assets and problems.** Rehabilitation is about protecting natural stream assets and improving or creating other assets. An asset is any aspect of the stream already in good enough to meet your goal. Many stream assets are threatened by stream problems, or have already been degraded. In this step you identify the main assets, degraded assets, and problems
5	Setting priorities: which reaches and problems should you work on first?	**Set priorities**. Which reaches of the stream have the highest priority for attention? Contrary to current practice, you would not usually start with the most damaged reaches, but with preserving the best ones

STEP	KEY QUESTION	ACTION
6	What are your strategies to protect assets and improve your stream?	**Develop strategies**. Identify and list the things that you can do to protect and improve the important assets in the reaches that you identified as a high priority in the last step
7	What are your specific and measurable objectives?	**Set measurable objectives**. From the options defined in step 6, create detailed objectives that will be the core of your rehabilitation plan
8	Are your objectives feasible?	**Check feasibility**. Are the objectives described in step 7 feasible? Many factors, such as cost, politics, and undesirable consequences for other users of the stream will force you to alter the priorities that you have identified. At the end of this step you will have settled on a final list of problems to treat
9	What is the detailed design of your project?	**Design the details**. In step 6 you identified the general methods that you would use to treat problems. You know need to develop a detailed design. What specific things do you need to do to achieve your objectives? These can range from doing nothing at all, to planning controls, or flow manipulation, to complete channel reconstruction
10	How will you evaluate your project?	**Plan the evaluation**. Measurable objectives were defined in Step 7: these now become the basis for evaluating the project. Importantly, our practical evaluation procedure emphasises that not all evaluation need to be detailed an expensive
11	How will you plan and implement your project?	**Schedule and supervise works**. The plan needs to be implemented by developing a time line, allocating responsibilities, finalising funding, doing the works, and organising the evaluation schedule
12	Has your project worked?	**Assess and maintain project**. The final step in the procedure is to maintain the work that has been done, and to set a point in the future at which the project will be formally assessed using information gathered in the evaluationplan

One other aspect of the discussion presented by Rutherfurd, Jerie and Marsh (2000) is particularly useful at this point. They provide a useful schematic (Figure 4.1) which illustrates the rehabilitation process in the context of catchment scale, suggesting that the '*chronological hierarchy of the steps in a project is matched by a spatial hierarchy...That is , the big end of the planning (vision, setting priorities, and problem definition) should concentrate on the regional or whole-of-catchment scale. As the planning moves to identifying solutions, detailed designs and evaluation, the focus tends to move down in scale to a group of reaches, a single reach , or a single group of stakeholders'*.

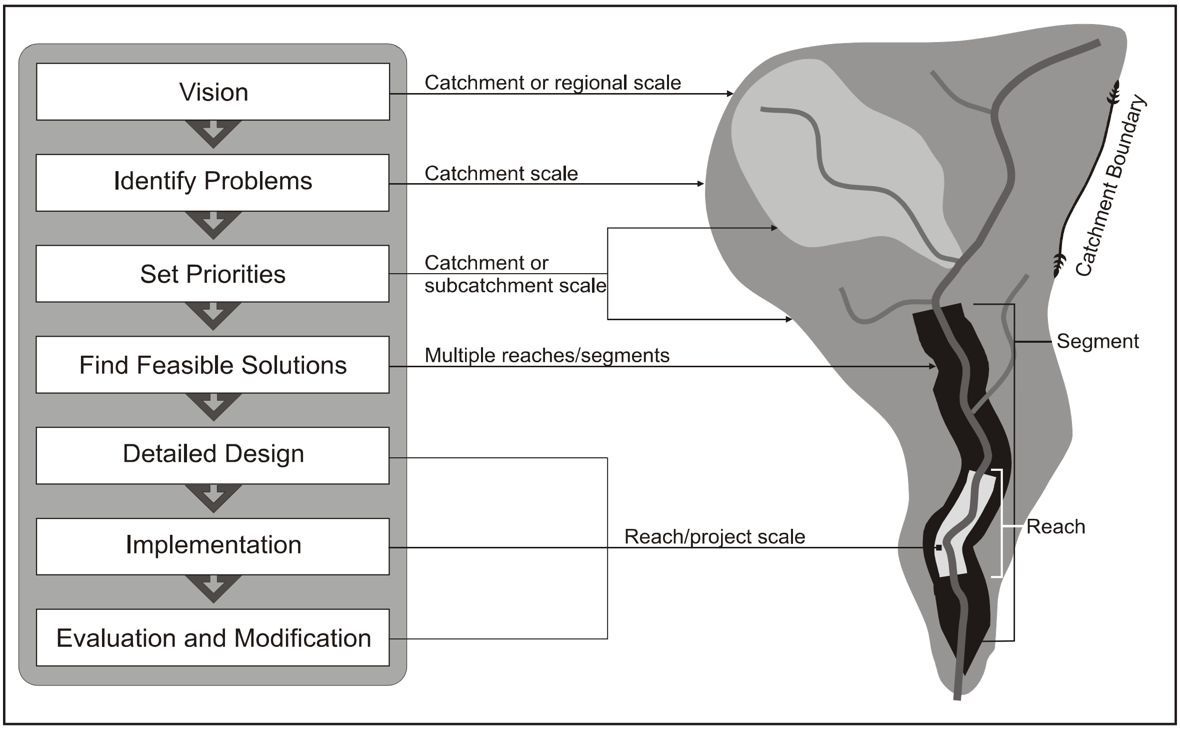

Figure 4.1 : Rehabilitation in the context of catchment scale (Rutherfurd, Jerie & Marsh 2000)

As indicated earlier the proposed framework represents an extension of the planning procedure developed by Rutherfurd, Jerie and Marsh (2000). This has been done to make links to existing techniques and procedures developed by South African researchers explicit. The principal differences lie in a more rigorous treatment of vision and goal setting (Rogers & Bestbier 1997) and some attention given to the importance of attempting to predict or evaluate the consequences of the intervention, particularly for the downstream reaches. This latter aspect is of significance with respect to the requirements of the Environment Conservation Act (Act No 73 of 1989). A further area where the approach could be extended is use of the concept of 'thresholds of potential concern' as given by Rogers and Bestbier (1997), as part of the monitoring and evaluation procedure. Figure 4.2 illustrates the procedure which is discussed further below.

(i) Develop a vision

The earlier discussion alluded to the importance of developing a vision. Indeed this is of such importance that Rutherfurd, Jerie and Marsh (2000) separate this out into two steps in their procedure; firstly *developing* the vision and secondly *sharing* the vision. These two steps have been combined for our purposes. This step requires strategic thinking; it requires identification of interested parties, allies and opponents. Stakeholder analysis may be an appropriate technique for helping plan the approach, but the the fundamental activity that this step requires is building support. As Rutherfurd, Jerie and Marsh (2000) have noted, '*most stream rehabilitation projects are at least as much about people as they are about science and construction* '.

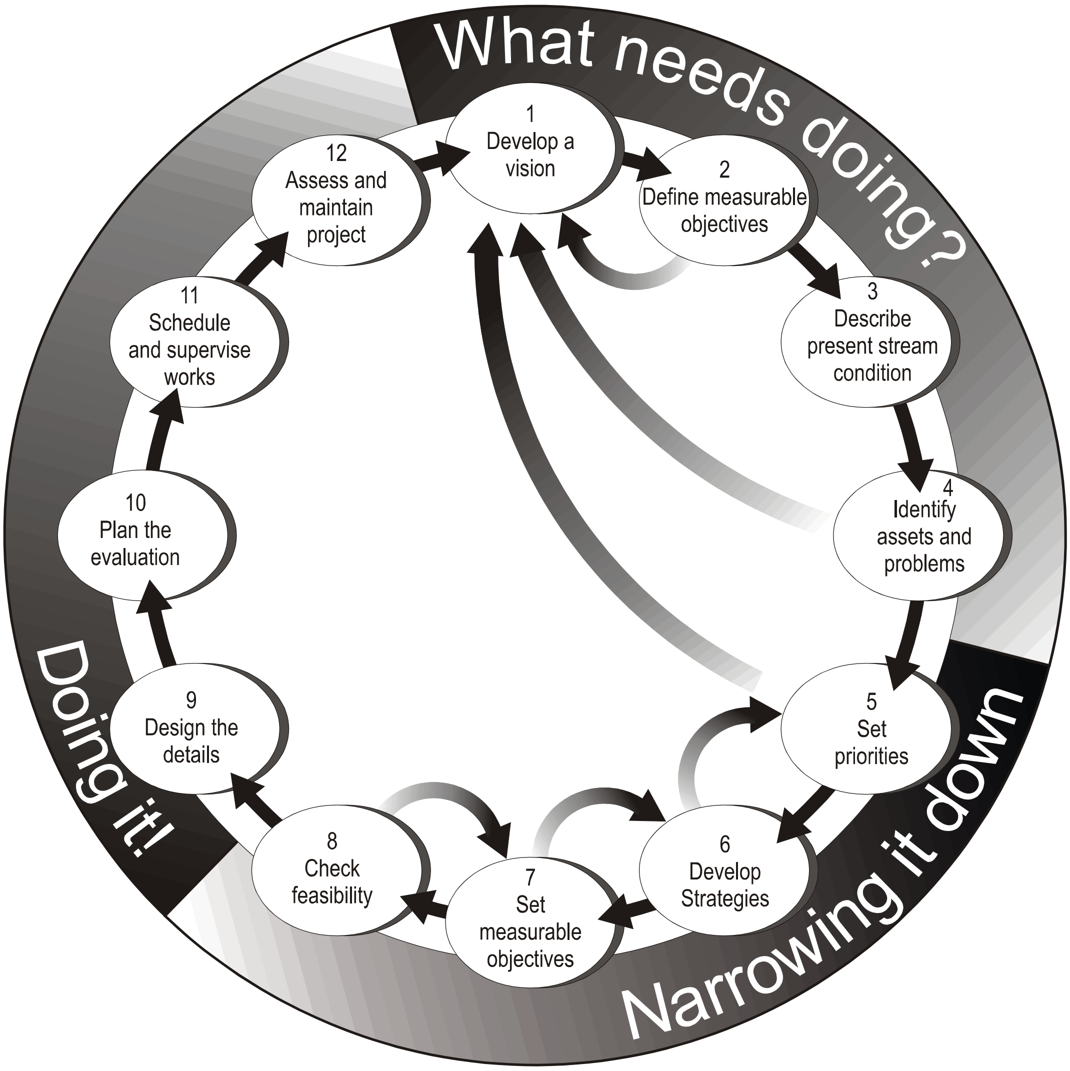

Figure 4.2: A proposed framework for river rehabilitation planning and management in South Africa (*after* Rutherfurd, Jerie & Marsh 2000)

(ii) Defining measurable objectives

Whilst the vision or goal will serve to provide a long term target, and hopefully, inspiration, a yardstick is required to provide a measure of progress. The earlier discussion has stressed the need for rehabilitation to be firmly based upon explicit and measurable ecological objectives.

Rogers and Bestbier (1997) present an approach for implementing goal-oriented resource management system which has been used both in the context of riparian and floodplain management, as well as for setting broader conservation objectives. The procedure involves breaking down an organisations 'vision' into 'objectives' enabling the definition of achievable institutional and conservation goals. The procedure includes a goal maintenance system which ensures that once goals are set, these are met, revised and audited and any resultant changes are re-integrated into the management process. An important concept in the approach is the definition of 'thresholds of probable concern' (TPCs), which are specific management indicators associated with management goals. For example if a management problem is the terrestrialization of the riparian zone, a possible TPC might be the ratio of terrestrial species to riparian species along the macro-channel floor (Mackenzie, van Coller & Rogers 1999). This is expressed in such that it can form part of a routine monitoring programme, and as an effective means of alerting managers to undesirable change in the system (Table 4.2).

Table 4.2: Approaches to setting measurable objectives (Rogers & Bestbeir 1997)

THE OBJECTIVES HIERARCHY

The hierarchy begins at the coarsest level with the organisation's "vision" for management. This protocol provides a step-by-step process for decomposing the vision into a series of "objectives" of increasing focus, rigour and achievability. The finest level of the hierarchy is defined by achievable goals which may be either "institutional goals" or "conservation goals". Institutional goals define achievable targets for maintaining institutional structures and processes. Conservation goals define endpoints for ecosystem management. The higher level vision and objectives serve upper management levels with statements of strategic intent, while the low level goals provide on-the-ground managers with specific, spatially and temporally bounded, targets. These targets are termed *Thresholds of Potential Concern* and act as amber lights to warn managers of possible unacceptable environmental change.

THE GOAL MAINTENANCE SYSTEM

The Goal Maintenance System provides an interactive internal auditing system to promote interaction between managers and ensure feedback between managers and scientists. The fundamental purpose of the Goal Maintenance System is to ensure that once acceptable goals have been set, they are met, revised, audited and, where necessary, reintegrated into the management process. Proper documentation of decisions taken and the reasoning behind them will provide the institutional memory to keep future management "on track" Rogers & Bestbeir (1997)

(iii) Describing the present stream condition

Several methods are available for evaluating stream condition. The purpose of this is twofold, firstly it provides a useful 'baseline' prior to the start of rehabilitation, and secondly it is necessary to establish how different the stream is from the target conditions set in the vision and objectives. Some of these methods are :

- Index of Stream Condition (ISC) (Ladson & White 1999)
- Riparian, Channel and Environmental Inventory (RCE) (Petersen1992)
- Stream reconnaissance method (Thorne 1998)

Section 4.3 describes an approach developed within this research based on a modified form of the Peterson (1992) RCE method. The modified approach extends that of Peterson (1992) by distinguishing between left, right and in-channel habitats and also attempts to provide a means of mapping landscape scale features as part of the baseline assessment. Section 4.5 describes advances in mapping, also central to this step.

(iv) Identify assets and problems

Rutherfurd, Jerie and Marsh (2000) argue that the focus of river rehabilitation has traditionally been on identifying problems and damage to streams. These authors call for a re-evaluation of this approach; stream managers should rather concentrate '*on identifying, preserving, improving and creating natural assets in streams*'. Knowing what the natural assets of a river system are, and how they should be protected is thus a key requirement.

Challen's (2001) approach discussed below provides a means of identifying and mapping assets and problems. Furthermore it attempts to also integrate landscape scale assets into planning for river rehabilitation. Blanché (2002) (Section 4.6) provides a means of identifying those riparian assets which may be of particular importance in the amelioration of the quality of agricultural runoff, while Horswell (2002) (Section 4.7) suggests a method for identifying sites for the attenuation of sediment.

(v) Set priorities

Rutherfurd, Jerie and Marsh (2000) suggest that '*it is far more efficient to preserve streams and reaches that are still in good condition, rather than concentrating on fixing what is already degraded. It is very important to attack the right problem in each reach, which may not be the most obvious (such as erosion) or the easiest to fix (such as riparian vegetation)*'. Asset protection should thus be the principal focus of rehabilitation.

Several of the research products reported on below have been designed to assist in this process. Schoeman (2001) (Section 4.4) provides a method for determining priorities for streambank rehabilitation while Horswell (2002) (Section 4.7) presents a range of methods for identifying priorities for sediment control.

(vi) Develop strategies

Strategies for rehabilitation are the specific rehabilitation measures that are selected for implementation together with the process and timing of their implementation.

Schoeman (2001) presents a decision support system for selecting techniques for streambank stabilisation (Section 4.4). Blanché (2002) provides a technique for rehabilitating riparian zones to achieve a high level of nitrate removal (Section 4.6), while Horswell (2002) illustrates how riparian zones can be sized to act as a buffer and trap sediment (Section 4.7).

The remaining steps in the process are not considered further here as they relate to implementation of the strategies, and the physical implementation of rehabilitation measures was seen to be beyond the scope of this research project.

4.3 A protocol for describing present stream condition, mapping assets and problems

Challen (2001) presents a method for mapping stream condition and identifying assets and problems which has been developed further (Appendix A). The first step of this protocol is the identification of landscape-scale assets. Aerial photography at an appropriate scale is obtained and all patches and corridors of natural vegetation are delineated from the broader matrix of land use. These patches and corridors, are digitised using an appropriate GIS. Each patch or corridor is then given a score of between zero and four for each of the attributes indicated in Table 4.2, and a total score is derived for each patch or corridor which is the sum of the weighted component scores. For details on how each criterion is scored see Appendix A.

Table 4.2 : Scoring criteria for patches and corridors and the weightings used to determine a final asset value score

PATCH SCORING CRITERIA	WEIGHT	CORRIDOR SCORING CRITERIA	WEIGHT
Size	0.4	Width	0.3
Edge-area ratio	0.2	Gap frequency	0.25
Shape	0.2	Links to patches	0.25
Connectivity	0.2	Length	0.2

In this way each patch or corridor is assigned a score which reflects the importance of that component in the landscape. These scores can be further modified on the basis of the quality of the vegetation, for example, the extent of alien invasive vegetation (Appendix A).

The second level of mapping suggested by Challen (2001) is the identification of broad vegetation types. At the broadest scale this could be through determining which Acocks (1988) Veld Types are present, or alternatively which Low and Rebelo (1996) Vegetation Types are present. Other approaches may include identification of the Bioresource Units (Kwazulu-Natal only) or the use of finer scale vegetation maps. The purpose of this stage is to determine whether any landscape-scale zonation in vegetation is present. Having determined whether any vegetation boundaries exist, these are then digitised together with the river network. Rivers are digitised in a manner that enables the slope of the river to be calculated for the river segment between each contour interval. Each river segment is then classified according to the geomorphological classification scheme presented by Rowntree, Wadeson and O'Keeffe (2000). The vegetation zonation and the river geomorphological zonation together provide the basis for the identification of appropriate river segments and reaches.

The third and final level of asset mapping involves the assessment of the quality of river banks, riparian vegetation and the quality of the instream habitat. Challen (2001) adopted the approach described by Petersen (1992), which has been refined further (Appendix A).Various criteria are scored for river reaches of 25m, 50m or 100m (depending on the required level of resolution or homogeneity of river length). Scores are obtained for the quality of the left bank, right bank and instream habitats, and enable the 3 components of each reach to be classified on a 5 point scale from poor to excellent. These scores are linked to the digitised river network and permit maps of instream and riparian zone assets to be plotted.

The three approaches allow a combined map of instream and riparian assets, landscape scale patches and corridors, and significant vegetation and geomorphological zonation to be prepared. Important reaches can be identified as can reaches which pose a threat to adjacent reaches.

4.4 A prototype DSS for streambank rehabilitation

One of the criteria used in Challen's (2001) approach is the stability of the left and right banks of each reach. If reaches in a particular area have been mapped according to this technique, a map of the river network showing relative streambank stability can be plotted. Schoeman (2001) has developed a prototype decision support system which can then be used to identify rehabilitation measures for unstable banks (Appendix B). The approach would be to undertake a site inspection at each of the reaches which have been noted as having a bank stability problem. A field assessment sheet comprising 8 criteria is completed and results in a bank severity assessment score of between 8 and 40 for the site being derived. At each site a value and a threat rating is also determined based on the approach of Heron *et al.* (1999) and Rutherfurd *et al.* (1999). The threat and value ratings enable the determination of a priority score for the site, and rehabilitation of the banks should proceed on the basis of these priorities. The final step is to use the set of flow charts to derive an appropriate rehabilitation technique or set of techniques. The bank stability score is used as an integral part of the flow chart process. The guidelines include structural measures for the riverbank as well as revegetation techniques for the banks and riparian zone.

4.5 Advances in mapping and delineating wetlands

4.5.1 Use of magnetic susceptibility mapping

Watson (2002) undertook preliminary testing of the use of magnetic susceptibility as an indicator of wetland boundaries (Appendix C). The basis for this approach is that wetland soils are typically leached and accordingly are characterised by lower iron contents than the terrestrial environment. The magnetic susceptibility meter provides an indication of the magnetizability of the area under the sensor, with much lower values recorded for gleyed soils. Appendix C provides a complete description of the initial testing of the approach.

4.5.2 Wetland mapping through the use of satellite imagery

Pillay (2002) focussed on developing a methodology for the accurate and efficient delineation of wetland areas using satellite imagery and other relevant spatial datasets. A brief synopsis of his findings is provided here, for further details consult Pillay (2002). Both summer and winter LANDSAT ETM+ satellite imagery covering the study area of the Midmar sub-catchment were processed using various image classification techniques. These included the supervised, unsupervised and level slicing classifications. The accuracy of each technique was tested against the only existing verified wetland dataset that covers the study area. A ground truthing exercise was also undertaken.

The different classification techniques resulted in different classification accuracies when compared to the verified wetland dataset. Accuracies for the different classification techniques were as follows: unsupervised 20 class classification (summer) 55%, (winter) 39%, unsupervised 255 class classification (summer) 71%, (winter) 47%; supervised classification (summer) 65%, (winter) 41%; level slicing classification (summer) 65%, (winter) 45%. The inaccuracies could mostly be attributed to a change in land cover as there seems to be an overall loss of wetland areas. However, the ground truthing exercise resulted in higher classification accuracies especially with unsupervised 255 class classification.

This study concluded that LANDSAT ETM+ satellite imagery was useful for detecting wetlands areas during summer by using a fine classification technique (255 class). A finer classification technique is also suited for the detection of both large and small wetland areas. Major recommendations include: the use of summer imagery in a high rainfall period; the unsuitability of using winter imagery due to the spectral confusions created; the use of high resolution satellite sensors (SPOT) for monitoring purposes while lower resolution sensors (LANDSAT) should be used for mapping; the increased use of topographical modelling for wetland detection; the use of an appropriate scaled land cover database and the use of field verification exercises for comparing classifications.

4.6 Riparian buffers in nitrate attenuation

Riparian zones are recognised globally for their function in water quality amelioration. Yet despite the growing literature there is little consensus on how to design, assess and manage these riparian buffer zones especially for nitrate attenuation. Blanché (2002) consequently undertook a literature review of world-wide research into the nitrate attenuation efficiencies of riparian buffer zones and created a database of studies (Appendix D). Two key processes responsible for immobilising and/or removing nitrate from surface and subsurface flows are generally recognised in the available literature, namely: vegetative uptake and the process of denitrification. A comparison of the available riparian studies indicated that there are similar characteristics in riparian buffer zones that may be responsible for enhancing these key mechanisms. Studies where there was shallow lateral subsurface or uniform surface water delivery pathways, vegetation of close structure and composition, high organic matter in the soils and fluctuating soil surface saturation rates showed the most significant nitrate attenuation efficiencies.

The research suggested that these similarities can be used to both assess a riparian landscape for its potential to attenuate nitrate, and to size a riparian buffer zone specifically to meet this function. A set of proposed guidelines based on the findings of the literature review attempt to illustrate how riparian pollution control recommendations can be achieved. These guidelines are an example of how to assist a farmer or similar landowner in achieving good nitrate removal efficiencies from a riparian buffer zone. The guidelines work through three steps, which help to establish and prioritise management zones; assess each zone's potential for nitrate attenuation; and determine adequate riparian buffer widths for each management zone. A case study was used to illustrate the practical application of the guidelines. Full testing of these guidelines was not within the scope of the research, however the guidelines are an indication of how information regarding riparian function can be applied to a system to determine effective management of water resources. For further details see Appendix D.

4.7 Riparian buffers in sediment attenuation

For a full discussion of this component see Horswell (2002) and Appendix E. A brief overview is provided below. It should be noted that while this component was developed and tested in an a forestry land use it is equally applicable in any agricultural setting.

Establishing the erosion potential for commercial forestry areas is readily accomplished through the application of existing models. Process based erosion models generally have greater data requirements than the empirically derived USLE-based models. Given the paucity of data available, the latter approach was adopted. Two methods of topographic sub-factor derivation were investigated, those associated with the RUSLE (Renard, Foster, Weesies & McCool 1991) and the Unit Stream Power method presented by Moore and Burch (1986). The USLE models were applied excluding the P factor, so as to develop an index that has not implicit criticisms of the land management practices of the landowners. The C-factor was also omitted, since the forestry activities do result in the regular removal of all vegetation from compartments, during harvesting, or as the result of catastrophic fires. The result of this modelling exercise is a spatial and relative measure of potential soil erosion and is called the Sediment Supply Index. Providing the resolution of the input data is adequate, this index can be used for compartment level erosion control. It allows the development of site-specific erosion control recommendations.

Since no existing methods identifying delivery risk areas existed, a method was developed based on principles and factors identified in the literature. This model yielded the Delivery Risk Index. It is based on the following road, stream and topographic factors; road-stream adjacency, road-stream intersections, road surface erodibility, road surface condition, and terrain morphology. Additionally, methods for identifying topographic assets, in terms of sediment attenuation, were developed. This index, called the Sediment Attenuation Index, identifies areas likely to act as sediment traps, based on the topography in which they occur. These three indices can be used, in conjunction with one another, to develop integrated sediment management strategies, addressing the problem at source and during transport.

However, prioritisation of areas for management intervention using continuous surface, landscape-based indices is difficult. It is necessary to relate sediment production to the stream to which it will be delivered. To accomplish this the study area was divided into micro-catchments. The mean Sediment Supply Index per catchment was divided by the stream length draining each of the micro-catchments to derive an index of sediment loading to streams. This index is useful in identifying priorities for management intervention across the landscape. To satisfy practical application requirements, specific recommendations regarding the required buffer widths to act as an efficient, final defence against sediment delivery to the watercourses are required. The micro-catchments form the basis of the analysis for developing buffer-width recommendations. The mean slope and sediment supply, for each catchment, is used to develop buffer width recommendations for the streams draining the catchments, using a method developed by Karssies and Prosser (2001).

The application of the modelling results, at both landscape and compartment levels enable tactical and operational management strategies to be developed. The approach was developed using readily available national datasets, and with the operational needs of the forestry industry as a departure point. It is hoped that this contribution in the pursuit of sustainable forestry will be implemented.

4.8 Alien vegetation and rehabilitation

4.8.1 Perceptions of invasive alien plants and the importance of a shared vision

The eradication of alien vegetation is a major challenge for most river systems in South Africa. February (2002) investigated perceptions of river and catchment management in a small rural watershed in the Western Cape province of South Africa. With a river length of only 19 km the Rondegat catchment spans just 3 groups of stakeholders with less than 10 representative individuals. In the upper reaches the catchment is a wilderness area under the control of Cape Nature Conservation. On the boundary of this former forestry area there is an innovative land reform project where the beneficiaries of the land are the former Cape Nature Conservation forest workers. This is a community of approximately 40 individuals and the small village and associated land is about to be transferred into a Trust. Downstream of the land reform project the land use is agricultural, with 4 commercial citrus farmers.

February (2002) interviewed all stakeholders concerning their attitudes to catchment and river management, and particularly the management of alien invasive tree species in the river and riparian zones. His study highlighted considerable differences between stakeholder groups, and in some cases, polarised viewpoints. No mechanism existed for stakeholders to exchange views, solve problems or work towards a common vision; and indeed many stakeholders held views concerning alien plants which are not supported by current scientific understanding. February's (2002) research illustrates the considerable challenge of local scale river rehabilitation and the critical importance of the first step of the river rehabilitation planning process. It is clear that successful river rehabilitation will be contingent upon stakeholders learning to communicate with each other. A platform for dialogue is required, as are mechanisms for conflict resolution and the provision of correct information concerning invasive alien plants. Sustainable river management will be dependent on a negotiated shared vision where varied stakeholder interests are understood, respected and accommodated.

4.8.2 Economics of alien vegetation eradication

Cooper (2001) undertook a cost-benefit analysis of alien vegetation removal from riparian zones in the Mhlathuze catchment, KwaZulu-Natal, and in so doing provides a methodology for planning such activities to ensure that they are cost-effective (Appendix F).

4.9 A database of trees, shrubs and grasses for riparian zone rehabilitation

A preliminary database of trees and shrubs, as well as grasses and wetland plants has been established. This database has been structured as two separate tables as the information available for trees and shrubs is slightly different to that of grasses and wetland plants. Key attributes of the database are indicated below in Table 4.3. A report for each of the two types of tables is given overleaf.

Table 4.3 : Structure of the database and number of records

TREES AND PLANTS			**GRASSES, SEDGES, WETLAND PLANTS**		
Genus	Species	Variety	Genus	Species	Variety
Common names	Other names		Common names	Other names	
Habitat	Biome		Habitat	Biome	
Vertical riparian position			Status description		
Rooting characteristics			Light requirements		
Propagation methods			Succession		
Perenniality			Perenniality		
Frost tolerance			Soil requirements		
Comment			Comment		
Total number in database = 66			**Total number in database = 105**		

GENUS: *Buddleja*

SPECIES: *salviifolia*

VARIETY/spp: -

COMMON NAME: Sagewood

OTHER NAMES: Saliehout(A); iLoshane(Z); iLothane, iGqange(X); molalatau(Ns)

HABITAT: Forest margins and in evergreen forests; rocky outcrops, rocky grassland and along watercourses (especially with permanent water); usually at higher altitudes; naturally absent from the lowlands of Kwazulu-Natal and Transkei (Eastern Cape); flourishes in shade and/or full sun

BIOME: Forest; Thicket; Grassland (except in the Freestate); Fynbos; Nama-Karoo (except in the Northern Cape); Succulent Karoo (except western Northern Cape)

PROPAGATION: Easily grown from seed or cutting, the cutting method being the best method of propagation; cutting made from hardwood and treated with a root stimulating hormone powder; plant cutting in river sand and keep moist (they usually strike after about 2-3 weeks); transplant into nursery bags filled with a mixture of riversand and compost (5:1); growth rate (600-800mm per year)

VERTICAL RIPARIAN-POSITION: Small tree(4-8m)

PERENNIALITY: Semi-deciduous to evergreen

ROOT CHARACTERISTICS: Vigorous rooting growing even in flowing water; valuable tree for stabilising embankments

FROST DESCRIPTION: Totally frost resistant

COMMENT: Leaves browsed by eland, kudu, bushbuck, impala and grey duiker (for the first three seasons young plants should be protected from game); attracts many insects as well as bees making it a good tree for bee farmers; visited by at least 15 butterfliy species when in flower, but host only to the African leopard butterfly; quick to recover after fires; wood used for spear shafts and fishing rods; also used for magical and medicinal purposes - roots used in remedy for coughs and colic, and the leaves are used in an infusion for sore eyes; fresh or dried leaves can be used as a tea (best drunk without milk); Sagewood adapts well to soil and climactic conditions; ideal for protecting water sources when planted in and around the sponge areas or the eye of a fountain; drought-resistant; the appearance of this tree in a treeless grassland is a good indication that scrub or forest will eventually establish (if fire is excluded)

GRASS AND SEDGE SPECIES

GENUS: *Aristida* **SPECIES:** *junciformis*

VARIETY/ssp: - **COMMON NAME:** Gongoni Three-awn

OTHER NAMES: Wire grass(E); ngongoni-steekgras(A)

HABITAT: Clay soil in vleis, wet places mostly in poor, gravelly soil on slopes; high altitude mountainous parts with high rainfall; (due to heavy grazing this grass is dominant in the grazed thornveld of Coastal Forest and Thornveld; sometimes in the thornveld which replaces Dune Forest; dominant through grazing in the sourveld of Pondoland Coastal Plateau Sourveld; in the thornveld of'Ngongoni Veld; in the sourveld of Highland Sourveld; in the sourveld of Natal Mistbelt 'Ngongoni Veld; in the southern coastal part of Coastal Fynbos; occasionally in the Southern Variation of Cymbopogon-Themeda Veld; in the Turf Highveld To Highland Sourveld Transition; Bankenveld to Turf Highveld Transition;sometimes in the grassveld of Highland Sourveld to Cymbopogon-Themeda Veld Transition; sometimes in the Near-Bankenveld Variation of North-Eastern Sandy Highveld; sometimes in the Eastern Variation of Bankenveld; occasionally in the grassveld of Piet Retief Sourveld; in the Natal Sour Sandveld)

STATUS DESCRIPTION: An increaser III grass **LIGHT:** -

VALUE DESCRIPTION: Low grazing value **SUCCESSION :** A climax grass

PERENNIALITY: A perennial tufted grass (grows for longer than five seasons)

COMMENT: Grows in most types of soil; excellent ground cover; one of the best grass types for brooms

FOREST BIOME	☐
FYNBOS BIOME	☐
GRASSLAND BIOME	☐
SAVANNA BIOME	☑
THICKET BIOME	☐
NAMA KAROO BIOME	☐
SUCCULENT KAROO BIOME	☐

SANDY SOILS	☑
CLAY SOILS	☑
GRAVEL SOILS	☐
LOAM SOILS	☑
FERTILE SOILS	☑

Chapter 5: CONCLUSIONS AND RECOMMENDATIONS

5.1 Conclusions

The field of river rehabilitation or restoration has experienced considerable growth in the last decade, particularly in Europe, the United States of America and in Australia. In contrast while there is a growing research interest in river rehabilitation in South Africa, very few significant rehabilitation projects have been undertaken and there is a lack of guidelines specific to South Africa. One of the significant areas of progress in Australia has been the development of a framework for planning rehabilitation projects. This framework was adopted, with slight modification, as the basis for river rehabilitation planning in the project and specific research projects were undertaken to develop components of a decision support system to assist in the planning and implementation of rehabilitation projects. Key developments included:

- An approach for mapping landscape scale assets.
- A methodology for identifying and mapping wetland boundaries from satellite imagery, as well as a new field-based approach to be used in conjunction with the current wetlands delineation procedures.
- A technique for identifying and mapping riparian, stream bank and in-channel assets and problems at the scale of a river reach.
- A GIS based protocol for identifying priority river reaches for rehabilitation and buffer establishment for sediment control, particularly relevant to the sugar and forestry industries.
- A protocol for assessing the nitrate attenuation potential of riparian zones, as well as a protocol for sizing riparian buffers to achieve a 65% reduction in nitrates, particularly relevant to commercial agriculture.
- A prototype decision support system for selecting appropriate techniques for:
    - streambank rehabilitation
    - riparian zone rehabilitation
- A database of appropriate plant species for rehabilitation in South Africa

It should be stressed that these research products were developed on the basis of limited testing and should therefore not be seen as definitive approaches.

A secondary objective of the project was the development of capacity. Development and enhancement of capacity in river rehabilitation and management was achieved through the following means:

- Inclusion of the approach, protocols and decision support systems as a 3-day module within the Integrated Catchment Management elective in the CEAD Masters Programme in 2000 and 2001. This resulted in 15 students being trained in the fundamental principles of river rehabilitation, 3 of which came from previously disadvantaged backgrounds.

- Ten of these students received further mentoring and training as they elected to undertake their dissertation research within the framework of this WRC Project. Four of these students came from previously disadvantaged backgrounds. Four of the eight students who have completed dissertations thus far, received distinctions for their research products.

- The training course in river rehabilitation in 2002 resulted in a further 20 people being trained, 6 of which came from previously disadvantaged backgrounds.

5.2 Recommendations

The various papers presented in the appendices of this report provide comprehensive recommendations for further research, development and testing of the techniques and protocols and will not be repeated in this overview. For further detail refer to the appendices and dissertations.

(i) Catchment-scale implementation, testing and refinement

This research project represented an initial level of investigation aimed at developing a set of tools and approaches that would have general applicability in South Africa. They have been developed for application in principally agricultural landscapes, and for streams of third order or less. The principal recommendation emerging from this research is that the techniques and protocols should be tested in a relatively small catchment (<$300km^2$) and through implementation of the rehabilitation planning framework with stakeholders in the catchment. Undertaking this exercise on a catchment basis with an emphasis on establishing priorities for action will provide a rigorous basis for evaluating the utility of the techniques and protocols and will assist in identifying further development needs. Such an exercise could form a sound basis for the development of a catchment management plan.

(ii) Establishment of regional (provincial) centres of expertise

This research project has resulted in the accumulation of a considerable set of resources on river rehabilitation and management. The project has also generated a fair amount of expertise and a number of developing techniques and protocols. Establishing regional centres of expertise would provide a node for the continued development of the discipline and also a resource for stakeholders to access.

Chapter 6 : REFERENCES

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APPENDIX A

ASSESSING RIPARIAN HABITAT: AN APPROACH FOR PLANNING REHABILITATION

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Abstract

Some of the functions of riparian habitats important in preserving the ecological integrity of ecosystems include sediment filtering, nutrient cycling, maintenance of biodiversity, and aquatic and terrestrial habitat provision. Many of these functions have been greatly undermined by poor land management practices and other human impacts. Many riparian areas require rehabilitation, protection and management to restore some of their previous ecological functions.

Experience in Australia suggests that the mapping of assets and problems will assist in determining priority areas for rehabilitation. This research addresses the mapping of riparian habitat assets and problems, and aims to achieve a habitat assessment approach that is appropriate in the South African context. Existing habitat assessment methodologies were reviewed and formed the basis of a proposed approach. The approach assesses habitat assets and problems from a landscape scale (macroscale), a reach scale (intermediate scale) and a site scale (microscale). In the landscape scale assessment, boundaries of corridors and patches are mapped. Various attributes of these corridors and patches are assessed, scored and weighted to determine an asset value for each unit. This process results in the identification of important features of the landscape. The purpose of the intermediate scale mapping is the identification of local scale vegetation boundaries and the segmentation of the river landscape into longitudinal zones of similar geomorphological character. The micro-scale assessment provides a weighted score per individual reach for each of the banks as well as the channel. On the basis of the assessment, threats and assets can be identified and particular reaches can be prioritised for rehabilitation.

1 Introduction

Riparian lands are complex ecosystems which include the land, plants, animals and a network of streams within them (Croonquist & Brookes 1991; FISRWG 1998; Askey-Doran 1999). They perform a number of ecological functions such as modulating stream flow, storing water, cycling nutrients, filtering sediments, and providing food sources; habitat and movement pathways for aqautic and terrestrial insects, birds and animals (Croonquist & Brookes 1991; Malanson 1993; Rutherfurd *et al.* 2000). The habitat provided by riparian areas is largely dependent on the ecological health and integrity of plant communities. These plant communities are a valuable source of energy for the biological communities, with a multiplicity of vertical and horizontal structures that provide diverse habitats and support biodiversity (Lovett & Price 1999).

Many natural riparian landscapes have become degraded through human activities such as agricultural practices, development, settlement, water abstraction, damming and encroachment on river systems (National Research Council 1992; Lynch & Catterall 1999). Many riparian areas have become divided into isolated, shrinking habitat patches. The growing understanding of riparian function has promoted a thinking towards riparian land rehabilitation. Traditional approaches to riparian habitat rehabilitation often focus much time and effort on the most degraded areas. More recent studies have indicated that protecting high asset value areas first may be a more successful approach. Australian researchers (Brierley 1999; Ladson & White 1999) are advancing this hypothesis by mapping riparian habitat asset and problem areas. But existing methodologies for riparian habitat assessment neglect to consider the relationship between the riparian areas, and the adjacent landuse activities. Furthermore, these methodologies do not address prioritisation of riparian habitats for rehabilitation.

This paper presents a habitat assessment methodology which is intended as an integral component of the process of developing a strategic action plan for the rehabilitation of riparian areas. The habitat assessment methodology should assist in prioritising riparian areas through the mapping of assets and problems, and must enable the identification of priorities for rehabilitation.

2 Macroscale assessment

The concept of habitat encompasses the ecological integrity and biodiversity of an area, where natural levels of plant productivity are maintained, where native biological diversity is evident, where natural rates of soil erosion occur, where natural nutrient cycles are maintained, and where healthy communities are present (Thorne 1993). In general, processes that occur at a landscape level can have a fundamental deterministic impact on the ecological integrity and the biological diversity of a riparian habitat. An understanding of the dynamics of a catchment at a landscape level is critical for riparian rehabilitation. Furthermore, riparian patches of habitat should be considered from a landscape perspective if priority areas are to be identified. The patch-corridor-matrix paradigm for analysing land mosaics has proven useful in understanding habitat processes that occur at a landscape level (Forman & Gordon 1981, 1986; Saunders *et al.* 1987; Merriam 1990). This paradigm allows for every element in a landscape to be readily identified as a patch, a corridor, or a background matrix (Forman 1991). Each of these in turn is characterised by attributes such as shape, area, width, and connectivity. Specific arrangements patches, corridors and background matrixes define the functional flows and movements of energy and materials through the landscape, such as habitat, migration routes, and breeding grounds.

Patches of natural vegetation surrounded by various landuses where natural vegetation is absent, function much like islands. This is usually referred to as the patch concept (Begon *et al.* 1996). Patch populations function within the patch and between the patches. The corridor concept refers to the use of corridors to migrate between patches (Forman 1991). These corridors may be communication or transport networks, streams, fence lines, or strips of vegetation linking patches. Corridors linking patches maintain genetic diversity, and allow for colonisation and recolonisation of habitats.

The structure and dynamics of riparian and stream habitat is determined by the surrounding watershed (Frissel *et al.* 1986), and it is therefore difficult to isolate riparian processes and functions from those that occur at a landscape level. When assessing riparian habitat, it is necessary to gain an understanding of the arrangement and structural patterns of riparian patches, corridors, and landuse activities within the catchment under study. The cumulative impacts of human activities and landuses on riparian habitat can be better identified with an understanding of the study area from a macroscale or landscape perspective.

A macroscale assessment of habitat has been developed, where aerial photographs and orthophotographs are used to identify and evaluate land mosaics through four steps. The following information is required:

- recent aerial photograph, preferably a scale of 1:10 000 (for vegetation)
- orthophotograph, preferably a scale of 1:10 000 (for contours)

STEP 1: GEOGRAPHIC SETTING AND BIOME-TYPE IDENTIFICATION

Step 1a: Describe geographic setting

This enables the user to become familiar with the study area prior to the field evaluation. The general topography and river networks should be identified, and the climate for the region described.

Step 1b: Identify the biome-type of the study area

The biome-type identification for the area can be achieved using for example, the biome classification by Acocks (1988) and/or Low and Rebelo (1996). Identification of the biome will facilitate in decision making regarding rehabilitation efforts, such as vegetation type selection for bank restoration.

STEP 2: LANDUSE IDENTIFICATION

Step 2a: Identify and categorise landuses, using numerical values

The landuses within the study area should be highlighted on the aerial photograph, where individual landuses are categorised using numerical values. For example:

Category	1	=	Grazing/pasture
Category	2	=	Cropland
Category	3	=	Settlement
Category	4	=	Undisturbed land
Category	6	=	Communication and transport networks

STEP 3: PATCH ANALYSIS

Step 3a: Identify natural vegetation patches

Using the orthophotograph and recent aerial photographs, highlight those patches undisturbed land where natural vegetation is evident (eg: Category 4 above).

Step 3b: Assign a patch asset value rating to each patch:

Patch asset value is determined by four variables (based on the ‘patch concept’):

- the **size** of the patch
- the **edge to area ratio** of the patch
- the **shape** of the patch
- the c**onnectivity** of the patch to other patches

Using Table 1, each variable for a particular patch can be rated and given an asset value score, where a score of zero indicates the variable has a low asset value, and a score of four indicates the variable has a high asset value. Patch rating is a subjective process, where asset patches within the area of study are to be identified. Therefore the ratings given to each variable are relative to the ratings given to the other patches within the area of study.

TABLE 1 Assistance sheet for achieving the patch component asset values for each of the four variables					
SIZE	Large area of undisturbed vegetation	Large area, but disturbed and dissected by human impact	Medium area	Small area	Very small area
EDGE: AREA RATIO	Very low	Low	Moderate	High	Very high
SHAPE	Circular	Circular	Circular but tending towards oblong	Oblong	Too small and narrow to form a shape
CONNECTIVITY	High degree of connectivity. No gaps and linked to many patches by corridors	Gaps in vegetation of large areas. Moderate level of connectivity to other patches. Connectivity affected by human activities	Low degree of connectivity	Isolated from other patches but has the potential for linkage	Extreme isolation from other patches. No corridors
ASSET VALUE SCORE	**4**	**3**	**2**	**1**	**0**

Step 3c: Achieve a patch quality rating for each patch

To achieve a patch quality rating score, the patch asset values for each of the four variables determined in **Step 3b** are weighted and summed (Equation 1). The score is then used in Table 2 to determine the quality of the patch. The variable ‘patch size’ is generally considered the most significant factor affecting the habitat quality of a patch. This variable therefore receives a greater weighting than the other variables.

$$PQRS = (S \times 0.4) + (EAR \times 0.2) + (SH \times 0.2) + (C \times 0.2) \qquad (1)$$

where

PQRS= patch quality rating score

S = patch asset value score for size

EAR = patch asset value score for edge:area ratio

SH = patch asset value score for shape

C = patch asset value score for connectivity

TABLE 2 **Achieving a patch quality rating**		
PATCH QUALITY RATING SCORE	PATCH CLASS	PATCH QUALITY RATING
4	I	Excellent
3	II	Very good
2	III	Good
1	IV	Fair
0	V	Poor

Step 3d: Create computer generated map of patch quality ratings

STEP 4: CORRIDOR ANALYSIS

Step 4a: Identify natural vegetation corridors

Using the orthophotograph and recent aerial photographs, highlight potential corridors where patches of natural vegetation may be linked (eg: Category 6 above).

Step 4b: Assign a corridor asset value rating to each corridor:

Corridor asset value is determined by four variables (based on the 'corridor concept'):

- the **width** of the corridor
- the **length** of the corridor
- the **connectivity** of the corridor
- the **degree of linkage** to patches created by corridors

Using Table 3, each variable for a particular corridor can be rated and given an asset value score, where a score of zero indicates the variable has a low asset value, and a score of four indicates the variable has a high asset value. Corridor rating is a also a subjective process, where asset corridors within the area of study are identified in much the same way as patch assets are identified (**Step 2**). Therefore the ratings given to each variable for a corridor are relative to the ratings given to the other corridors within the area of study.

TABLE 3 **Assistance sheet for achieving the corridor component asset values for each of the four variables**					
WIDTH	Very wide band of vegetation, low EAR	Wide band of vegetation, low EAR	Medium band of vegetation, moderate EAR	Narrow band of vegetation, high EAR	Very narrow band of vegetation, very high EAR
LENGTH	Very long	Long but interrupted by gaps	Short	Almost non-existent	Too fragmented to form a length

TABLE 3 Assistance sheet for achieving the corridor component asset values for each of the four variables					
CONNECTIVITY	No gaps corridor is continuous (eg: a road network)	low gap frequency, disruption of continuity	Gaps common, distance small between gaps	High gap frequency, large distance between gaps	Extremely high gap frequency, very large distance between gaps
CORRIDOR LINK TO PATCHES	Very high degree of linkage to very many patches (>8), links vital resource patches to other patches	High degree of linkage to many patches (>6), links vital resource patches to other patches	Medium degree of linkage to several patches (>4), links vital resource patch to individual patch	Low degree of linkage between two patches	No linkages of patches
ASSET VALUE SCORE	**4**	**3**	**2**	**1**	**0**

Step 4c: Achieve a corridor quality rating for each corridor

To achieve a corridor quality rating score, the corridor asset values for each of the four variables determined in **Step 4b** are weighted and summed (Equation 2). The score is then used in Table 4 to determine the quality of the corridor. The variables have been weighted according to their influence on corridor habitat quality.

$$CQRS = (W \times 0.3) + (L \times 0.2) + (CC \times 0.25) + (DL \times 0.25) \qquad (2)$$

where

CQRS = corridor quality rating score

W = corridor asset value score for width

L = corridor asset value score for length

CC = corridor asset value score for connectivity

DL = corridor asset value score for degree of linkages with patches

TABLE 4 Achieving a corridor quality rating		
CORRIDOR QUALITY RATING SCORE	CORRIDOR CLASS	CORRIDOR QUALITY RATING
4	I	Excellent
3	II	Very good
2	III	Good
1	IV	Fair
0	V	Poor

Step 4d: Create computer generated map of corridor quality ratings

3 Intermediate-scale assessment

Riparian habitat is greatly influenced by local characteristics of the river it surrounds. At an intermediate scale, the river and riparian habitats can be grouped into reaches of similar characteristics called segments. One method of grouping similar reaches together would be on the basis of slop and vegetation. The intermediate-scale assessment requires an orthophotograph (preferably 1:10 000) of the catchment.

STEP 1: SLOPE ASSESSMENT

Step 1a: Split the river network at each contour line and at the point of entry of each tributary

The river can be divided up into sections using an orthophotograph. A section is the stretch of river between two contour-river intersections, and a segment is the river between two tributaries or a length of river divided by any other systematic means.

Step 1b: Approximate gradient of each section

The approximate gradient of a river section can be calculated by dividing the contour interval by the length of the section (distance between the two contours) (Equation 3).

$$G = V/H \qquad (3)$$

where,

G = Gradient

V = Vertical distance (contour interval in meters)

H = Horizontal distance (distance between contours in meters)

Step 1c: Draw longitudinal profile of each segment

A longitudinal profile is a good visual aid, as it allows the user to identify pool/riffle sequences, or river deepening, or particle deposition and similar processes.

Step 1d: Classify segments into homogenous groups and create map

The segments can be classified into homogenous groups on the basis of their gradients. A gradient class ranking has been adapted by Rowntree *et al.* (2000). Each segment of river can be classed as per Table 5, and mapped accordingly.

STEP 2: VEGETATION TYPE ASSESSMENT

Step 2a: Classify vegetation types into homogenous units

Determine whether there are any local scale vegetation units, determine these boundaries and map. Map any riparian wetlands or any other features of special interest.

TABLE 5 **Classification of river segments into gradient classes (Rowntree *et al.* 2000)**		
GRADIENT CLASS	ZONE CLASS	CHARACTERISTIC CHANNEL FEATURES
> 0.1	**A:** Mountain headwater stream	A very steep gradient stream dominated by vertical flow over bedrock waterfalls and plunge pools. Normally first or second order. Reach types include bedrock fall and cascades
0.04 - 0.099	**B**: Mountain stream	Steep gradient stream dominated by bedrock and boulders, locally cobble or course gravel in pools. Reach types include cascades, bedrock fall, step-pool. Approximate equal distribution of 'vertical' and 'horizontal' flow components.
0.02 - 0.039	**C**: Transitional	Moderately steep stream dominated by bedrock or boulder. Reach types include plane bed, pool-rapid or pool-riffle. Confined or semi-confined valley floor with limited flood plain development.
0.005 - 0.019	**D**: Upper foothills	Moderately steep, cobblebed or mixed bedrock-cobblebed channel, with plane bed, pool-riffle or pool-rapid reach types. Lengths of pools and riffle/rapids similar. Narrow plain of sand, gravel or cobble often present.
0.001 - 0.0049	**E**: Lower foothills	Lower gradient mixed bed alluvial channel with sand and gravel dominating the bed, locally may be bedrock controlled. Reach types typically include pool-riffle or pool-rapid, sandbars are common in pools. Pools of significantly greater extent than rapids or riffles. Flood plain often present
0.0001 - 0.0009	**F:** lowland river	Low gradient alluvial fine bed channel, typically regime reach type. May be confined, but fully developed meandering pattern within a distinct flood plain develops in unconfined reaches where there is an increased silt content in beds or banks.

4 Microscale assessment

The quality of riparian habitat includes the instream ecosystem, river banks and surrounding vegetation. The Riparian, Channel and Environmental Inventory (RCE) is a methodology developed by Petersen (1992) to assess the condition of riparian habitat of principally lowland agricultural stream. It was been widely tested and found to be an appropriate index of stream health for streams of this nature. However, the RCE only provides a single score for a river reach and does not distinguish between the left and right river banks. This often results in an average score being obtained when one bank comprises a high value asset and the opposing bank a low value asset. The RCE methodology has therefore been slightly to include an assessment of both the left and right river bank, and the instream habitat. The microscale assessment requires that 16 indicators which define the condition of the river system (Table 6) are rated and quantified. The scoring system for this methodology of microscale habitat assessment follows the weighting system of the RCE very closely. The microscale assessment follows five steps.

TABLE 6 Indicators chosen for habitat assessment data sheet (at a microscale)	
RIVER BANK HABITAT	• Landuse adjacent to stream zone • Width of riparian zone from stream zone • Connectivity of bank vegetation • Riparian vegetation composition • Riparian vegetation structure • Stream bank structure • Bank undercutting • Level of erosion within riparian zone
INSTREAM HABITAT	• Artificial barriers • Channel sediments • Bed stability • Embeddedness • Canopy cover • Aquatic vegetation • Woody debris • Pool riffle ratio

STEP 1: IDENTIFY RIVER SECTION TO BE ASSESSED

Step 1a: Divide river section into 100 meter intervals

For each 100m interval, stand midway (at the 50m mark) and observe the upstream and downstream river and bank habitats within the 100m segment. Each 100m segment must be rated and scored as indicated in ***Step 2***, ***Step 3*** and ***Step 4***, using the microscale assessment data sheets (Table 7 and Table 9). The scores for each of the 16 indicators should reflect the actual observation made for the 100m segment. Once each of the 16 indicators have been rated for a 100m segment, the process is repeated until all 100m segments have been scored. There are two microscale assessment data sheets, namely; *River bank habitat* (***Step 2***), and *Instream habitat* (***Step 3***).

STEP 2: SCORE RIVER BANK INDICATORS

Step 2a: Determine a quality score for the left river bank habitat

Complete questions 1 to 8 of microscale data sheet (Table 7) for the left river bank. Sum the scores to achieve a total score out of a possible 230 (this can be done later).

Step 2b: Determine a quality class rating for the left river bank habitat

Using Table 8 to determine the quality class rating, a recommended action for the left river bank can be decided.

Step 2c: Achieve a quality score for the right river bank habitat

Complete questions 1 to 8 of the microscale data sheet (Table 7) for the right river bank. Sum the scores to achieve a total score out of a possible 230.

Step 2d: Achieve a quality class rating for the right river bank habitat

Using Table 8 to determine the quality class rating, a recommended action for the right river bank can be decided.

TABLE 7 **Microscale assessment data sheet for river bank habitat** (*Step 2*)				
INDICATOR	**CONDITION**	**RATING**	**SCORE**	
			Left bank	**Right bank**
1. LANDUSE ADJACENT TO STREAM ZONE	Undisturbed, consisting of forest, grassland or natural wetlands Permanent pasture mixed with woodlots and/or few row crops Mixed row crops and pastures Mainly row crops	30 20 10 1		
2. WIDTH OF RIPARIAN ZONE FROM STREAM ZONE	>35 meters 26 meters to 35 meters 16 meters to 25 meters 6 meters to 15 meters <5	30 20 5 1 0		
3. CONNECTIVITY OF BANK VEGETATION	No gaps (continuous) Limited gaps Moderate gaps Many gaps	30 20 5 1		
4. RIPARIAN VEGETATION STRUCTURE	High proportion single-stemmed woody plants Low proportion multi-stemmed woody plants Low proportion non-woody vegetation	25		
	Moderate proportion single-stemmed woody plants Moderate proportion multi-stemmed woody plants Moderate proportion non-woody vegetation	15		
	Low proportion single-stemmed woody plants High proportion multi-stemmed woody plants High proportion non-woody vegetation	5		
	Vegetation less than 1.5 meters in height	1		
5. RIPARIAN VEGETATION COMPOSITION	0% exotic vegetation 1 - 10% exotic vegetation 11 - 40% exotic vegetation 41 - 60% exotic vegetation >60% exotic vegetation	20 15 5 1 0		
6. STREAM BANK STRUCTURE	Banks stable, well vegetated Banks firm, but vegetated, loose soil aggregates Banks loose, sparsely vegetated, poor root densities Banks unstable, erosion evident, no vegetation	25 15 5 1		
7. BANK UNDERCUTTING	Little/no undercutting evident Undercutting only on curves, & at constrictions Undercutting frequent, undermining bank stability Severe undercutting along channel, bank collapse	20 15 5 1		
8. LEVEL OF EROSION WITHIN RIPARIAN ZONE	No evidence of erosion Little erosion evident (sheet erosion/small rills) Moderate erosion (deeper rills/ gully development) Extensive erosion (deep gullies/dongas)	20 15 5 1		
TOTAL QUALITY CLASS SCORE FOR LEFT BANK HABITAT *(Step 2a)* **AND TOTAL QUALITY CLASS SCORE FOR RIGHT BANK HABITAT** *(Step 2c)*			**/230**	**/230**

STEP 3: SCORE THE INSTREAM HABITAT INDICATORS

Step 3a: Determine a quality score for instream habitat

Complete questions 9 to 16 of the microscale data sheet for instream habitat(Table 9). Sum the scores to achieve a total score out of a possible 165 .

Step 3b: Determine a quality class rating for the instream habitat

Using Table 8 to determine the quality class rating, a recommended action for the instream habitat can be decided.

TABLE 8
Habitat quality class rating sheet for microscale assessment

CLASS	SCORE	EVALUATION	COLOUR	RECOMMENDED ACTION
QUALITY CLASS RATING FOR LEFT AND RIGHT BANK HABITATS (*Step 2b & Step 2d*)				
I	170 - 210	Excellent	Blue	Biomonitoring and protection of the existing status
II	130 - 169	Very good	Green	Selected rehabilitation efforts needed and monitoring for changes
III	90 - 129	Good	Yellow	Minor rehabilitation needed
IV	50 -89	Fair	Brown	Major rehabilitation needed
V	6 - 49	Poor	Red	Complete structural organisation
QUALITY CLASS RATING FOR INSTREAM HABITAT (*Step 3b*)				
I	135 - 165	Excellent	Blue	
II	102 - 134	Very good	Green	
III	70 - 101	Good	Yellow	
IV	39 - 69	Fair	Brown	
V	2 - 38	Poor	Red	
QUALITY CLASS RATING FOR TOTAL HABITAT (*Step 4b*)				
I	473 - 585	Excellent	Blue	
II	362 - 472	Very good	Green	
III	251 - 361	Good	Yellow	
IV	140 - 250	Fair	Brown	
V	8 - 139	Poor	Red	I

TABLE 9 **Microscale assessment data sheet for instream habitat** (*Step 3*)			
INDICATOR	**CONDITION**	**RATING**	**SCORE**
9. ARTIFICIAL BARRIERS (WEIRS, DAM WALLS etc.)	No artificial barriers Only barriers under extreme low flow Semi-permanent barriers drowned under moderate flow Permanent barriers drowned under extreme flow Permanent inhibition of aquatic biotic movement	20 10 5 1 0	
10. CHANNEL SEDIMENTS	Little channel enlargement resulting from sediment accumulation Gravel bars of coarse stones and well-washed debris, little silt Sediment bars of rocks, sand and silt common Channel divided into braids	15 10 5 1	
11. BED STABILITY	High bed stability, no evidence of erosion, infilling or deepening	25	
	Stable, but evidence of infilling & deepening, little bed erosion	15	
	Moderate bed stability: • INFILLING: Some fine sediment on bed & bars, channel accumulation of sediment at obstructions, reduced channel capacity by fine sediment, bed tending to flat;minor overbank siltation • DEEPENING: Little fine sediment in bed, minor erosion on both banks, deposition in pools, moderately steep bed, minor deepening	5	
	Limited bed stability: • INFILLING: High level of sediment on bed and bars (same size), channel accumulation of sediment at obstructions • DEEPENING: No evidence of sediment in bed, major deepening, steep bed	1	
	Extensive bed instability, extreme slumping, infilling, deepening	0	
12. EMBEDDEDNESS	Gravel, cobble & boulders 0 - 25 % surrounded by sediment Gravel, cobble & boulders 26 - 50 % surrounded by sediment Gravel, cobble & boulders 51 - 75 % surrounded by sediment Gravel, cobble & boulders 76 - 90 % surrounded by sediment Gravel, cobble & boulders >90 % surrounded by sediment	30 20 10 1 0	
13. CANOPY COVER	Excellent Good Average Poor None	20 15 10 5 1	
14. AQUATIC VEGETATION	Moss & patches of algae Algae dominant in pool, vascular plants along edge Algae mats present, some vascular plants, few mosses Algae mats cover bottom, vascular plants dominate channel	15 10 5 1	
15. WOODY DEBRIS	Abundant woody debris Numerous visible large pieces Few visible large pieces No visible large pieces	15 10 5 1	
16. POOL RIFFLE RATIO	Variety of pools and riffles Adequate sequence of pools and riffles Occasional sequence of pool and riffles Long distance between sequences No pools or riffles	25 15 10 1 0	
TOTAL QUALITY CLASS SCORE FOR INSTREAM HABITAT *(Step 3a)*			**/165**

STEP 4: DETERMINE A QUALITY RATING FOR TOTAL HABITAT

Step 4a: Score the total riparian habitat

Sum the left bank habitat quality score (***Step 2a***), the right bank habitat quality score (***Step 2c***) and the instream habitat quality score (***Step 3a***) to achieve a total habitat quality score out of a possible 585.

Step 4b: Determine a quality class rating for the total habitat

Using Table 8 to determine the quality class rating, a recommended action for the total habitat can be decided.

STEP 5: CREATE HABITAT QUALITY MAP

Table 8 assigns a colour to the quality class for each of the left bank habitat, right bank habitat and instream habitats. A map showing the quality rating for each of the three habitats can be generated using GIS techniques.

Conclusions

The three levels of assessment result in the landscape being categorised into distinct units with the threats and assets spatially represented. This enables the manager to consider which might be the priority reaches, or to identify where the significant assets are. Maps of single criteria (e.g. streambank stability) could also be plotted as a precursor to the site specific assessment (see Schoeman 2001).

However it should be noted that this methodology has not undergone extensive testing and development, and should therefore be used with caution. It should also be noted that the microscale assessment is based on the approach of Peterson (1992), which was specifically developed for lowland agricultural streams.

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APPENDIX B

A PROTOTYPE DECISION SUPPORT SYSTEM FOR THE SELECTION OF STREAMBANK REHABILITATION TECHNIQUES

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1 INTRODUCTION

It is well established that riparian areas are the critical buffer zones between land and water (Cairns 1995; Clarke 1991; LWRRDC 1998). They play an important role in the life cycle of many animals and plants, and provide a host of goods and services to society. These include, amongst others, water quality amelioration (Welshe 1991; Palone & Todd 1997), maintenance of biological diversity (Sullivan *et al.* 1987; Newbury *et al.* 1998; Simpson *et al.* 1982), erosion control (Gilliam *et al.* 1986; Veneman 1994; Bren *et al.* 1997; Klapproth 1999), and the often over-looked service of providing an aesthetically pleasing landscape (Kuska 1977; Litton 1977; Leopold 1969; Hoover *et al.* 1985).

These systems frequently comprise fertile soils and more moist conditions, and as a consequence are often targeted for use in intensive cropping and other forms of development. Over-engineering, pollution, over-abstraction and unsympathetic management have heavily contributed to the destruction of many streambanks, which is a cause of great global concern. As a result, these areas have become the subject of rehabilitation efforts costing considerable sums of money. For example, in England, the rehabilitation of a two kilometer stretch of the River Cole, which has restored more frequent flooding to adjacent fields and returned the river closer to its original condition, cost ₤140 000.

On another project in England, 500m of the River Skerne, where the creation of a new meander in the old, straight course, and the enhancement of the existing course cost ₤300 000 . In Japan US$200 million was recently spent to restore the waterways of Tokyo for recreational purposes (Gippel *et al.* 1998) and 1500 sites have been treated in a similar manner around that city. In the United States, the restoration of Biscayne Bay, a major Florida estuary is estimated to have cost in the region of US$ 24 million (Thorhaug *et al.* 1990), while in South Africa, the project to rid that country's riparian areas of exotic, water wasting species, is running into the millions of rand (Versfeld *et al*. 1998). Streambank rehabilitation is considered a fundamental component of catchment management and rehabilitation. Providing the means for making bank stabilization techniques more accessible to managers is an urgent priority.

One major hurdle, that stream managers face in the streambank rehabilitation process, is the selection of appropriate techniques. Managers are often presented with manuals containing a diversity of techniques (Table 1), however, they may not necessarily be completely certain as to the applicability of the techniques and wether they may match the erosive forces occurring on the streambank. The manager may therefore find himself confused due to the lack of guidance on the subject.

Table 1: Key riparian rehabilitation guidelines that have been produced to date

Title	Author(s)
Environmental Restoration: Science and Strategies for Restoring the Earth	Berger (1990)
Rehabilitating Damaged Ecosystems	LWRRDC (1999)
Riparian Land Management Technical Guidelines	Cairns (1995)
A Rehabilitation Manual for Australian Streams	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 Manual of Techniques	Vivash and Murphy (1999)

It follows therefore, that techniques are available to mitigate against bank instabilities (Table 1). 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. 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 the vice versa.

2 AIMS AND OBJECTIVES

Before the aims of the paper are laid down, the underlying principles must first be established. Recognizing the need to address the degraded state of our river systems:

- Riparian areas are assumed to provide several indirect benefits through the services that they provide (e.g. erosion control and water quality enhancement)
- A balance is struck between riparian area exploitation and restoration efforts, provided that consideration is also given to the economic, social, organizational, and institutional factors affecting riparian management.

The aim of the paper therefore, is to provide an approach which will guide users, both experienced and inexperienced, through a streambank rehabilitation exercise. It is aimed that the user is made aware of all aspects of river restoration and is encouraged to undertake the work holistically. The objectives of this research project were to:

(i) Review riparian rehabilitation and streambank restoration techniques and processes. Particular attention will be given to the recent technical guidelines produced by the UK, USA and Australia

(ii) Identify criteria for streambank rehabilitation technique selection

(iii) Consolidate information to a decision support system

(iv) Design a system for setting priorities between catchments or sites

(v) Undertake preliminary testing of the approach and evaluate its utility

(vi) Re-examine the underlying doctrine of the document in retrospect, and provide recommendations for future use.

3 METHODOLOGY

A priority setting model was compiled using the works of Heron *et al.* (1999) and Rutherfurd *et al.* (1999) as a basis. For each problem site along a river reach a value and a threat rating is determined according to Tables 2 and 3 respectively.

Table 2: 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			
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, natives present along both banks possibly with some grassed areas	Significant presence of understory exotics mixed with remnant natives. Native overstory generally remaining with some cleared grassed areas, or one side cleared with other virtually undisturbed.	Remnants of native understory. Understory dominated by exotics. Ground cover mainly consists of introduced exotics	Lacks one or more structural elements (Overstory, understory, ground cover, or macrophytes), 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 native vegetation, or some exotics or reduced cover or natives in wider corridor. Minor areas of disturbance with possibly some small areas of introduced grasses	Wide corridor of mixed natives and exotics, with the one side cleared and the other reasonably undisturbed and > 5m plus the height of the bank wide	Narrow corridor of native or exotic vegetation (< 5m plus the height of the bank wide)	Both sides cleared with introduced groundcover

Table 3: 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, natives present along both banks possibly with some grassed areas	Significant presence of understory exotics mixed with remnant natives. Native overstory generally remaining with some cleared grassed areas, or one side cleared with other virtually undisturbed.	Remnants of native understory. Understory dominated by exotics. Ground cover mainly consists of introduced exotics	Lacks one or more structural elements (Overstory, understory, ground cover, or macrophytes), 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

Rating	Very low threat	L ow threat	Moderate threat	High threat	Very high threat
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 native vegetation, or some exotics or reduced cover or natives in wider corridor. Minor areas of disturbance with possibly some small areas of introduced grasses	Wide corridor of mixed natives and exotics, with the one side cleared and the other reasonably undisturbed and > 5m plus the height of the bank wide	Narrow corridor of native 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 ans verges (< 10% presence)	Significant presence on banks and verges (40 - 80%)	Most of corridor infiltrated (> 80%)	

A priority score for each site is calculated by using the following formula:

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

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 must take precedence over site scores (Table 4):

Table 4: The rules which are an exception over the site scores, and must be used with site scores (adapted from Rutherfurd *et al.* (1999)

1. First priority must be given where the integrity of important structures are threatened, such as property, buildings, bridges or fords.
2. 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)
3. 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)

Within these three priority levels, scores are still applicable (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:

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

For a thorough and holistic streambank rehabilitation undertaking, a guiding process would be beneficial. An eleven-step process (Table 4) was adapted from Kapitzke *et al.* (1998) for this purpose. It provides a consistent strategy to address stream management issues at a regional scale, down to the design of suitable remediation of 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. It functions in the following manner:

Heron *et al.* (1999) priority setting model selects the most appropriate site to start the rehabilitation operation. SR-DSS assists in the choice of remediation strategy at the specific site. While the planning and design model adapted from Kapitzke et al. (1998) links the broader catchment and reach issues, Heron *et al.* (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 2. Without SR-DSS, the user of the adapted Kapitzke *et al.* (1998) 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 restoration work on any particular catchment. Together, Heron *et al.* (1999) priority setting model, SRDSS, and Kapitzke *et al.* (1998) planning and design procedure, go hand in hand to form an holistic approach. 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 minimizing 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 5: Planning and design procedure adapted from Kapitzke *et al.* (1998)

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 remediation objectives and constraints
	Step 6	Identify the remediation options and concept designs
Feasibility	Step 7	Feasibility designs and evaluation
	Step 8	Decide on the remediation program
Implementation	Step 9	Detailed design and implementation
Monitoring and maintenance	Step 10	Monitor and maintain
Review	Step 11	Review project

A field assessment sheet, using information provided by Thorne (1998) and others was also developed (Table 6). The field assessment sheet helps determines the type of intervention required on the basis of providing a numeric score between 8 and 40 reflecting the severity of bank instability for each site. This score acts as an input into the bank rehabilitation decision support system.

A flow chart-based decision support system of riparian bank restoration techniques was compiled from a literature review of numerous existing manuals designed for other parts of the world. Contributing documents will include those referred to in Table 1. A variety of streambank restoration techniques were gathered, classified and organized into the flow chart which guides users to the most appropriate technique according to the required objective (see Flowcharts).

The completed versions of the field assessment sheet, decision support system flow chart and priority setting model were tested in the case of the Foxhill Spruit in Pietermaritzburg, South Africa. The Foxhill Spruit is a small urban river which has been highly impacted by channel incision as a consequence of urbanisation and thus increases in the intensity and duration of flow peaks.

Table 6: Field assessment of bank stability

CRITERION	1	2	3	4	5
Bank height	< 1m	1m to 1.5m	1.5m to 2m	2m to 2.5m	> 2.5m
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	insignificant	mild	moderate	serious	very serious
Geotech failures and erosion	no geotech and little erosion, bar perhaps mild sheet erosion	no geotech faliures, perhaps sheet erosion or minor rilling	no geotech failures, major sheet erosion, major rilling or minor gullying	tension cracks < ½ bank height, geotech faliures (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, wide buffer, 80 to 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%

4 RESULTS

The approaches described above were implemented for 18 sites along the Foxhill Spruit. The priority scores, field assessment scores and final priority derived for each site are as follows:

Table 7: Priority scores, field assessment scores and final priority for each of the 18 sites

(PS=Priority Score, FAS=Field Assessment Score, FPS=Final Priority Score)

SITE	PS	FAS (FPS)	SITE	PS	FAS (FPS)	SITE	PS	FAS (FPS)
1	60	11	**7**	375	32	**13**	242	36
2	150	13	**8**	336	31	**14**	264	34
3	300	22	**9**	220	23	**15**	153	24
4	345	35	**10**	200	28	**16**	144	20
5	308	24	**11**	220	31	**17**	190	20
6	213	35	**12**	325	33	**18**	325	31

Table 8 shows the results of the flowchart based DSS applied to each of the sites. Also indicated are possible alternative rehabilitation measures not indicated by the DSS, annotated with explanations of why they are inappropriate for the site.

5 DISCUSSION

To attain a relatively robust confidence in the recommendations given by the decision support system, it needed to be tested. The final appraisal was conducted on the Foxhill Spruit, a tributary of the Mzunduzi river, which flows through the town of Pietermaritzburg, however, during the course of its development, tributaries of the Tugela River were used to guide the process and expose errors and complications within the decision support system.

Due to the small catchment size of the Foxhill Spruit, every site along its length could be inspected, rated with the field assessment sheet and priority setting model, prioritised, and given a list of techniques recommended by the decision support system. This enabled the entire process to be tested, from the framework, through to determining if sound recommendations were dispensed by the decision support system. The appraisal of the rehabilitation process has been broken into logical segments for simplification.

(i) Appraising the framework

The framework, within which the rehabilitation process may be set seemed to work well. It brings to the attention of the user, all the forces at play at the particular site. The testing of the framework could not be completed however, due to time and resource constraints and was only executed until step six, or where the decision support system was called on to recommend techniques. By going further than step six, considerable detail would have been necessary, and 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 and were found to place the process of prioritising, analysing and technique appraisal in a logical order. This helped simplify the process and enabled a ‘light to be cast at the end of the tunnel’ so to speak.

Table 8: Results of the application of the flowchart based decision support system

	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 plantings										○						○		
Branch packing									○									
Live fascines																		
Stone toe protection																		
Bank shaping & pl.				■				■			□	■						■
Joint plantings																		
Riprap				¶§ ¿●		¶§ ¿●	¶§ ¿●	¶§ ¿●			¶§ ¿●	¶§ ¿●	¶§ ¿●	¶§ ¿●				¶§ ¿●
Mattress cells																		
Vegetated geogrids																	○§ ¿	
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

Option chosen by DSS | **Possible option for this site**

(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. 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. Due to the badly degenerate state of the stream, degraded sites tended to stretch for considerable distances. It was where these sites merged with others, and different erosive processes were occurring, that it became difficult to distinguish one site from another. Different erosive processes occurring on a bank usually means different rehabilitation techniques would be required to match each process. This challenge was overcome by separating sites into those that would require a particular set of rehabilitation technique. This meant, that where two sites merged over a distance of, say 10 metres, the beginning and the end of each site would be taken where the dominant erosive force changed. Furthermore, the challenge of varying conditions at one site, was overcome by taking the dominant characteristic for the field assessment sheet.

(iii) Field assessment sheet

All circumstances that were encountered on the Foxhill Spruit were represented on the field assessment sheet. It is recognized, however, that the Foxhill Spruit illustrates only a fraction of the conditions that occur in the real world. For this reason, the user must proceed with caution and not take the field assessment score as an absolute assessment. Feedback is now needed from users who may encounter circumstances which are not represented on the sheet, and if there are any points of confusion. Arising from the possibility, that the score may misrepresent the degradation on the site, SR-DSS has inbuilt mechanisms to circumvent this chance. This will be discussed below. Testing on the Foxhill Spruit, however, produced field assessment scores which represented the degradation, or problems, on the site accurately. On the basis of this, the field assessment sheet, is judged as satisfactory.

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 1 where the field assessment scores (multiplied by 10) are plotted against the priority scores. A similar trend exhibited by the two lines can 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.

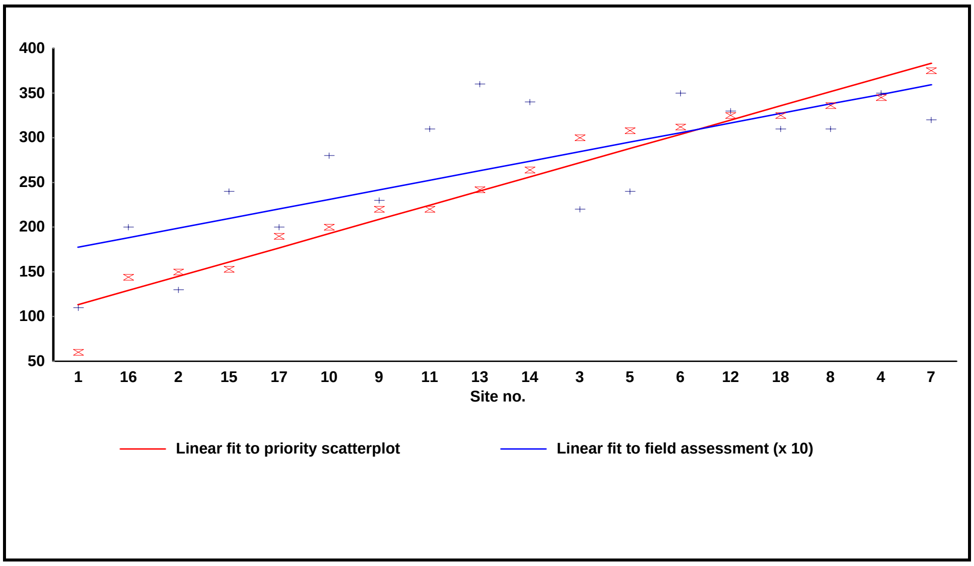

Figure 1: Demonstrates the similar trend in the scores reached by the field assessment sheet and the priority setting model.

(iv) Appraising the priority setting model

The outcome of the priority setting model was in line with Rutherfurd *et al.*, (1999), and this was taken as satisfactory. The problem with the priority setting process is that the desired outcome is quite subjective. It depends greatly on the resources and objectives of the user and what he is prepared to achieve. For this reason, the default priority was set at ecological and structural restoration of the streambank at least expense, with the augmented 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, that the rest of the catchment would receive attention. The priority setting model has performed well with respect to this. 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 carefully study and familiarise himself with the rules. Once accustomed to the rules, the priority setting model is fairly simple to use.

(v) The decision support system

The development of a decision support system has made it possible to effectively choose suitable riparian rehabilitation techniques for any stream in South Africa, this view based on the result of the testing procedure on the Foxhill Spruit. With this decision support system, the layperson is able to implement a rehabilitation program of his own, and customise it to his own objectives and constraints, instead of relying on a professional which would incur considerable cost. SR-DSS was designed to deal with all of the possible 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 streams, such as the effects of freeze/thaw, have been omitted, however, these may have to be incorporated at a later date 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 in the employ of SR-DSS, and makes available references which may be consulted for further information on each of the techniques. Furthermore, where vegetative techniques are required, the user may consult Table 6 for suitable riparian species in the area of choice.

For the selection of robust streambank rehabilitation techniques, which matched the erosive pressures, or the problems experienced on the site, the decision support system was found to be satisfactory. At all sites which needed intervention, be it from exotic species invasion through to large scale slumping, SR-DSS recommended appropriate techniques to combat the problem. To test whether another technique would not have been better suited at the site than the one recommended by SR-DSS, Table 7 was produced. This table lists all the sites needing restoration on the Foxhill Spruit against all the techniques suitable for streambank restoration. The techniques chosen by SR-DSS are marked in dark blue, and ones which are potential choices are marked in light blue. In each of the cases, as can be seen, SR-DSS chooses the most appropriate technique for the site. All the potential choices have some factor advocating against them.

Although the decision support system has its advantages, the user must throw caution when it is being used in the flowing situations. Where the degraded bank is above the height of three metres, for example, the user is advised to consult with a structural or civil engineer (this recommendation is built into SR-DSS). The physical capabilities of the recommended techniques themselves have their limitations, and must not be stretched beyond them. It is feared that their effectiveness decreases exponentially with every metre above three metres. The very nature of bank materials necessitates the use of rigid engineering methods in the region above three metres, which is the general rule of thumb, although this may vary depending on a number of variables such as cohesiveness, presence of roots, moisture content, *et cetera*. Possibly the most rigorous method of bank stabilisation at an engineer's disposal may be a concrete lining, should the situation require it.

The relative cost and difficulty of implementation also rises exponentially as the bank increases in height. Where the field assessment score is equal to, or above 36, the user is also advised to consult with an engineer (this recommendation is also built into SR-DSS). A score of 36 would usually imply that the bank is extremely vulnerable, and expert advice would be required for bank stabilisation. The techniques in the employ of SR-DSS are not designed for such 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 to deal with such situations.

As with the priority setting model, however, the Foxhill Spruit illustrates only a fraction of the conditions that occur in the real world, and caution must be exercised by the user. Testing, or use in more diverse settings, is now needed. Feedback is also needed for improvement and inclusion of circumstances that are not represented. On the basis of testing on the Foxhill Spruit however, it may be said, that the decision support system is able to yield sound streambank rehabilitation techniques on all South African streams, provided the above concessions are observed.

6 CONCLUSIONS AND RECOMMENDATIONS

- The decision support system can only be used on streambanks that are less than three metres high
- Where banks are greater than three metres high, or fall outside the design limits of the restoration techniques, users should consult a civil or appropriately qualified engineer
- SR-DSS effectively chooses streambank rehabilitation techniques
- SR-DSS helps bring the cost of rehabilitation down by replacing the professional at certain stages of the process
- SR-DSS needs to be extended further to include all aspects of degraded rivers such as bed stabilisation, and in-stream habitat
- It may be developed further into a computer based decision support system which would make it a very powerful tool
- It needs to be tested under more diverse circumstances, as yet it has only been tested on one river with a limited number and diversity of problems
- The priority setting model may be too complicated, and may need refinement for greater understanding by users
- 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 of Heron *et al.* (1999) as well as provide scores for SR-DSS. By using the field assessment sheet in place of the priority setting table, the process and time spent in the field would be made simpler and save time respectively
- Perhaps a weakness in SR-DSS is that it addresses problems experienced at the site or regional

problems and neglects addressing the cause of those problems which may be system-wide. It attempts to solve the problem by looking for causes on a regional basis, and neglects the possibility that those problems may be caused on a system-wide basis.

- Feedback from users is now needed so that improvements adjustments and additions may be made
- A well-known limitation in restoration 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) recognize 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.
- The development of a decision support system for the selection of streambank restoration techniques is hoped will be a distinct step forward in the field of riparian restoration in South Africa.

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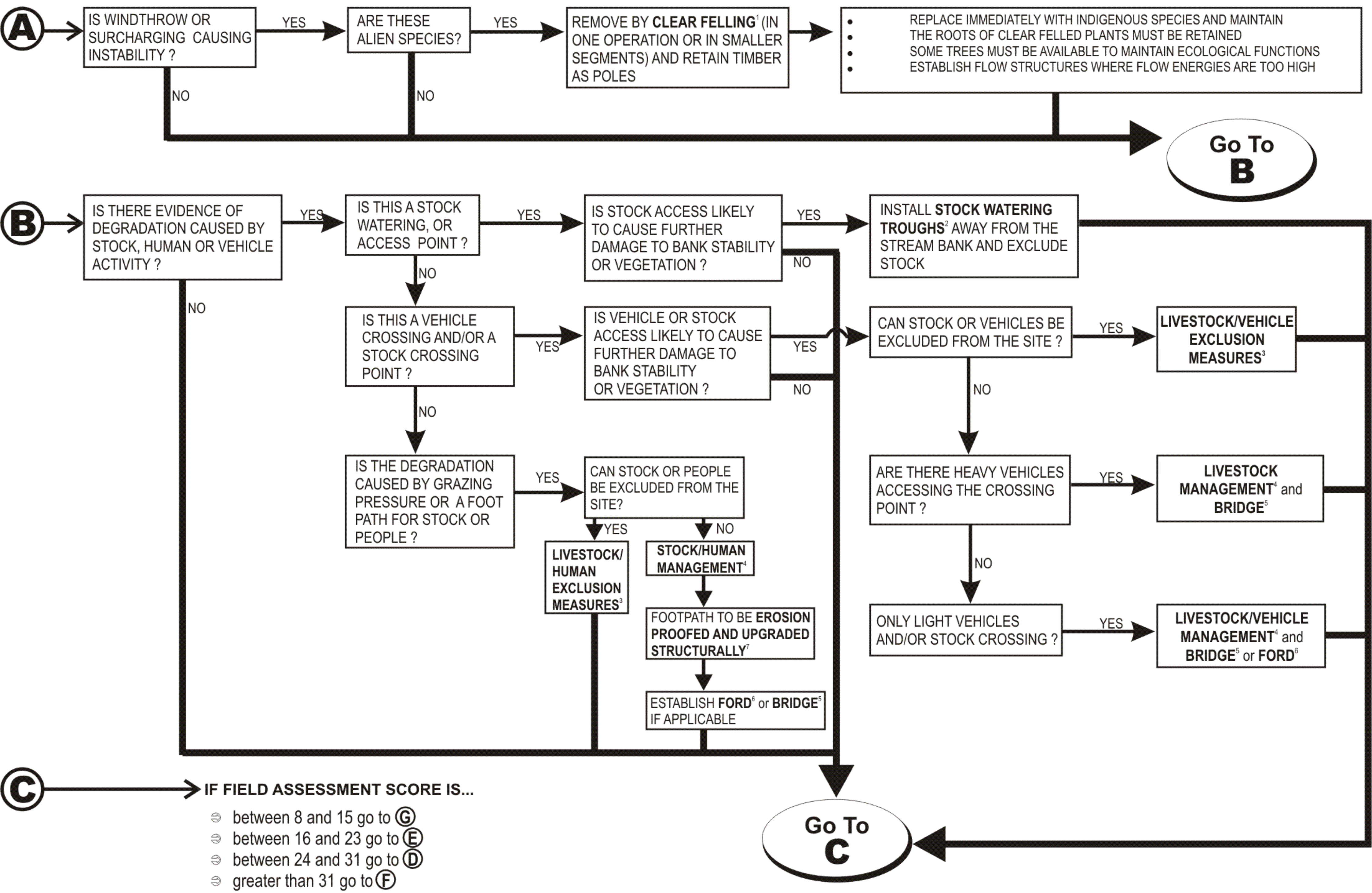
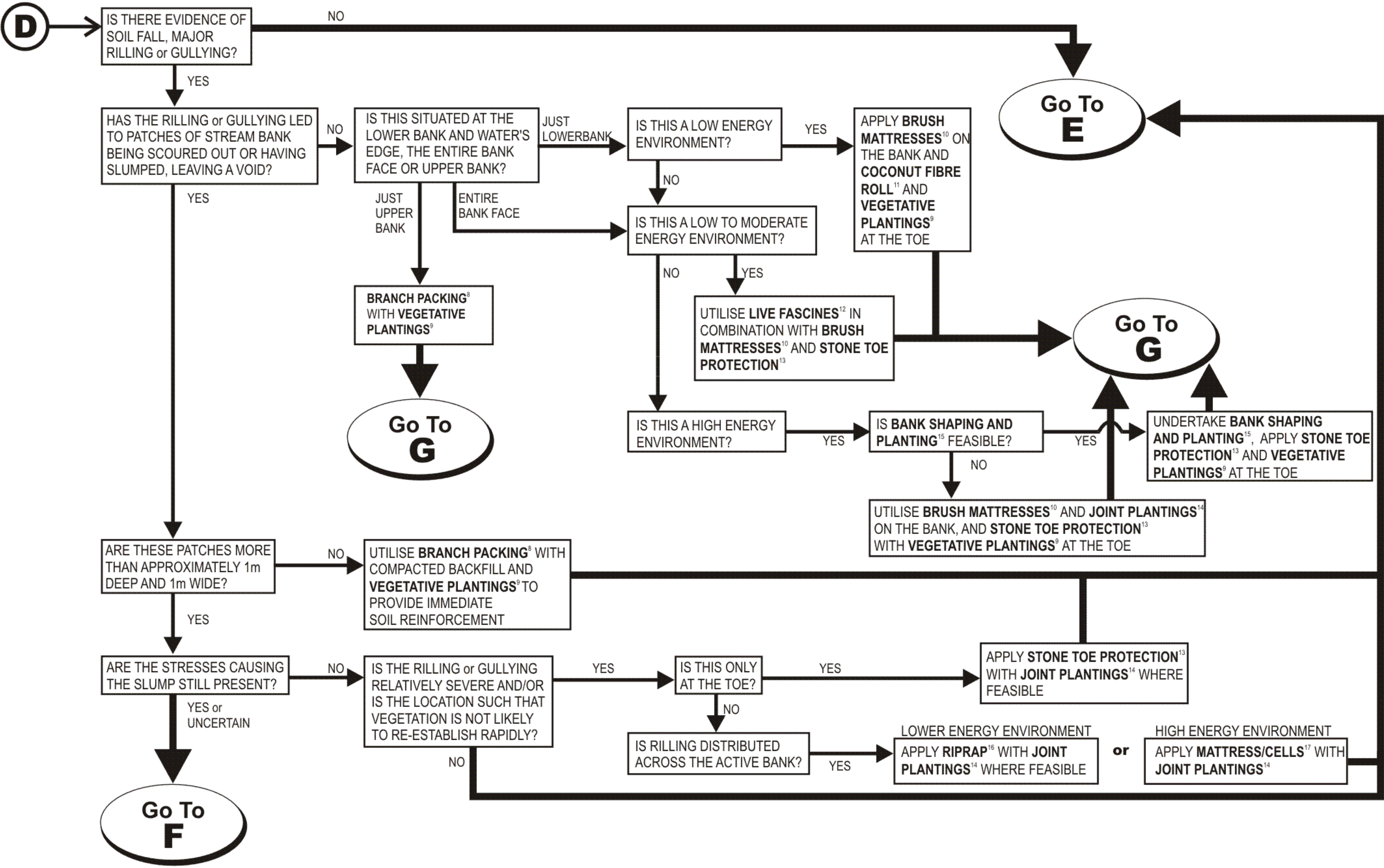
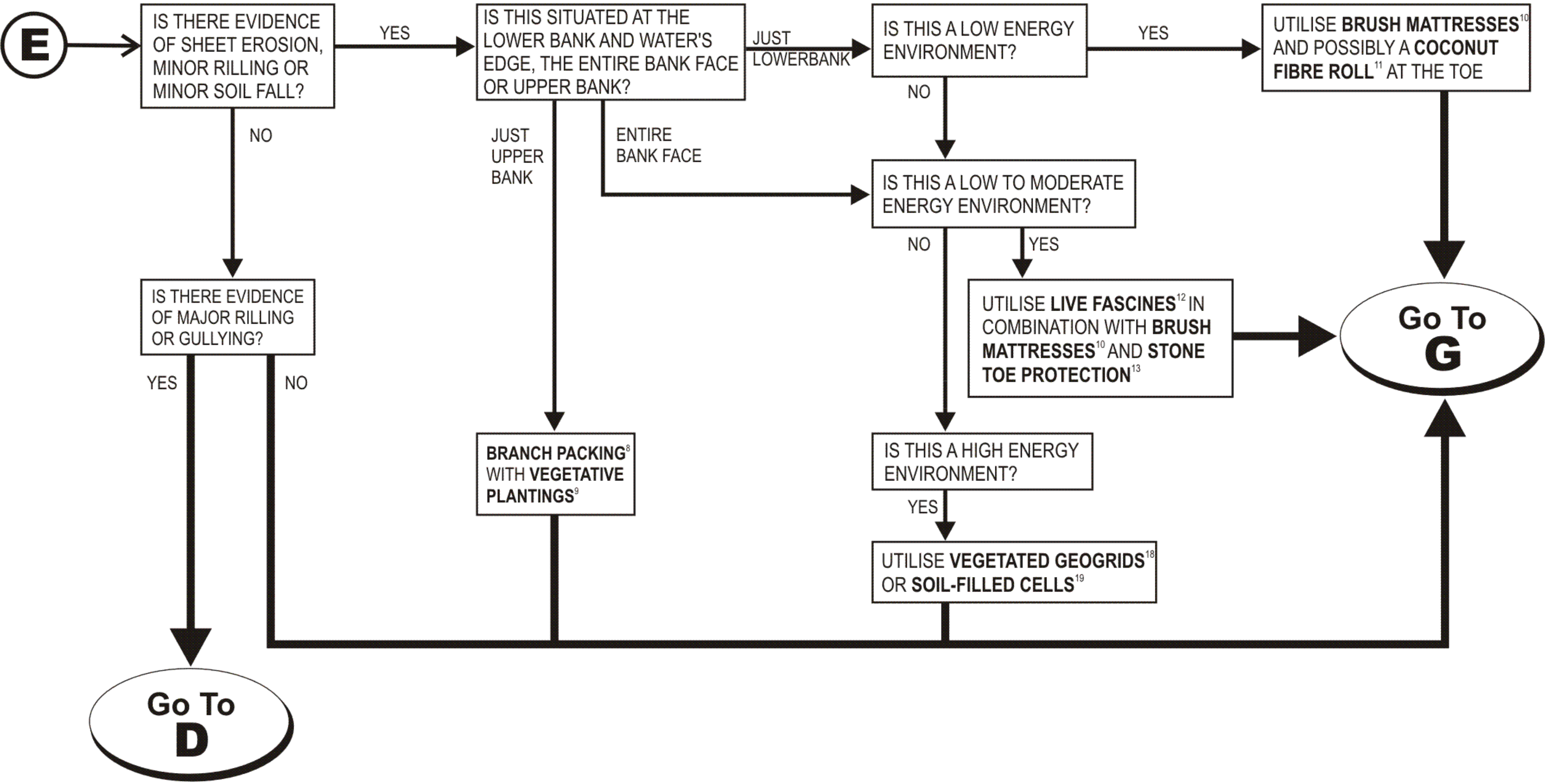
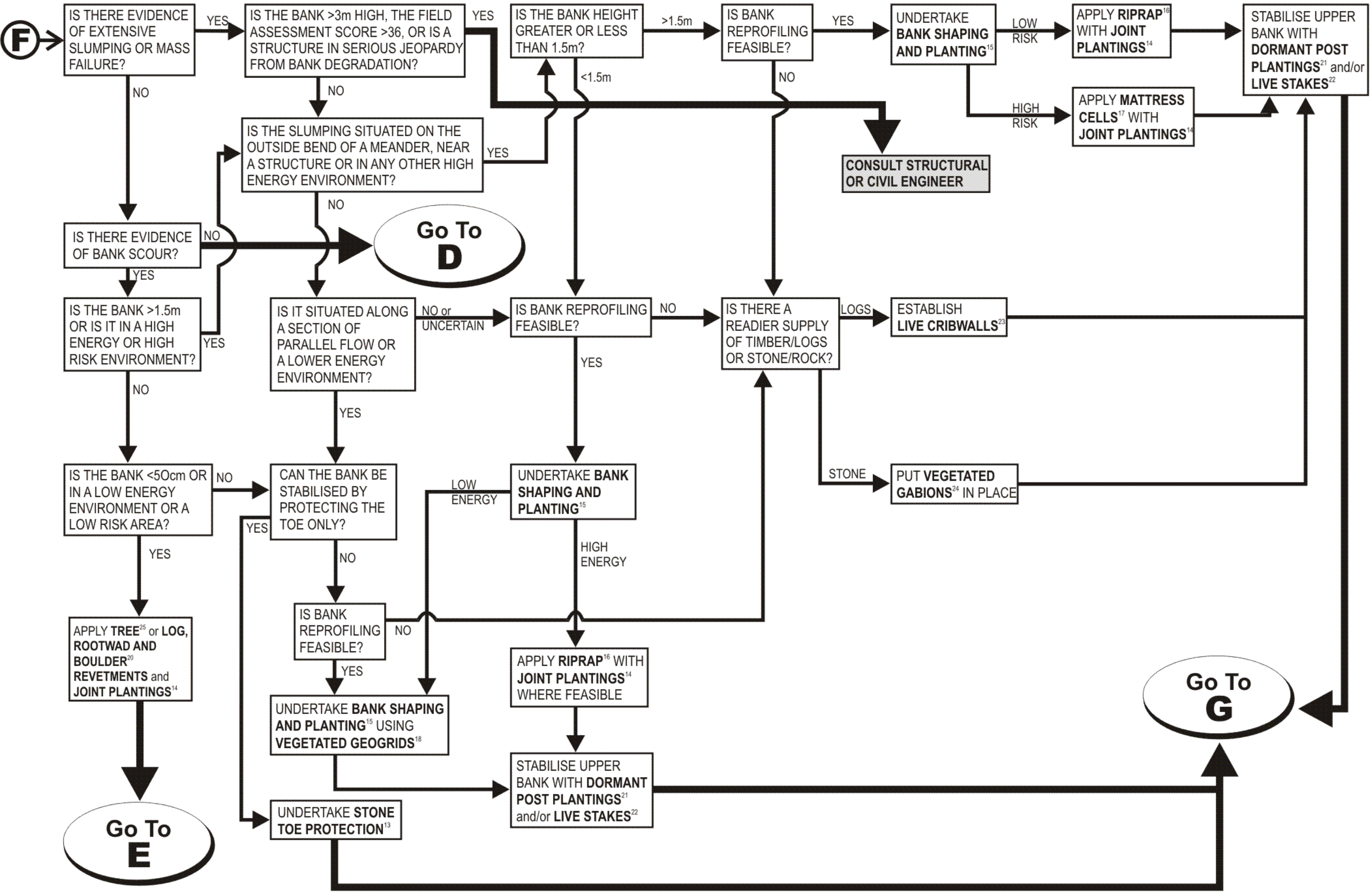
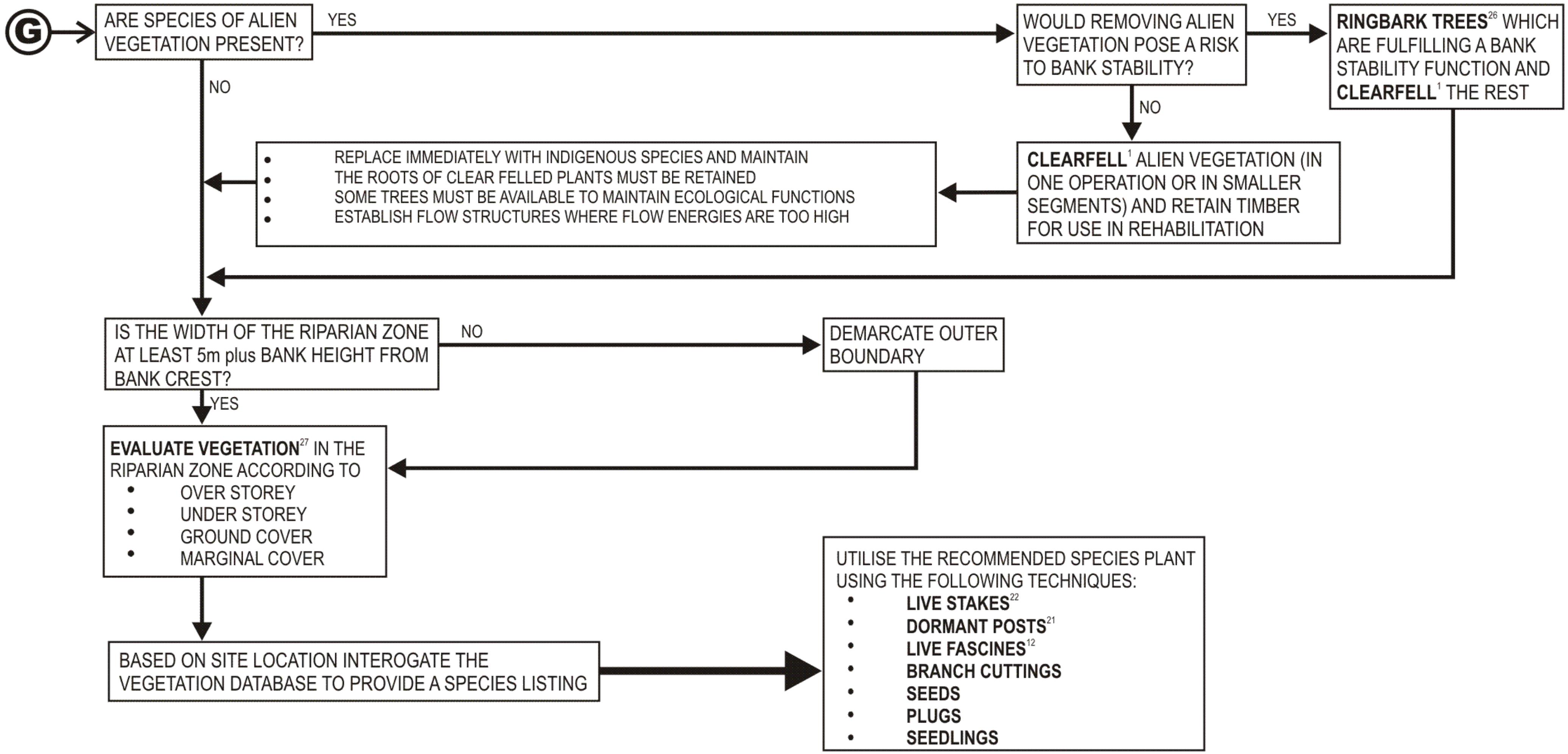

A
IS WINDTHROW OR SURCHARGING CAUSING INSTABILITY ?
YES
NO
ARE THESE ALIEN SPECIES?
YES
NO
REMOVE BY CLEAR FELLING[1] (IN ONE OPERATION OR IN SMALLER SEGMENTS) AND RETAIN TIMBER AS POLES
REPLACE IMMEDIATELY WITH INDIGENOUS SPECIES AND MAINTAIN
THE ROOTS OF CLEAR FELLED PLANTS MUST BE RETAINED
SOME TREES MUST BE AVAILABLE TO MAINTAIN ECOLOGICAL FUNCTIONS
ESTABLISH FLOW STRUCTURES WHERE FLOW ENERGIES ARE TOO HIGH
Go To B
B
IS THERE EVIDENCE OF DEGRADATION CAUSED BY STOCK, HUMAN OR VEHICLE ACTIVITY ?
YES
NO
IS THIS A STOCK WATERING, OR ACCESS POINT ?
YES
NO
IS STOCK ACCESS LIKELY TO CAUSE FURTHER DAMAGE TO BANK STABILITY OR VEGETATION ?
YES
NO
INSTALL STOCK WATERING TROUGHS[2] AWAY FROM THE STREAM BANK AND EXCLUDE STOCK
IS THIS A VEHICLE CROSSING AND/OR A STOCK CROSSING POINT ?
YES
NO
IS VEHICLE OR STOCK ACCESS LIKELY TO CAUSE FURTHER DAMAGE TO BANK STABILITY OR VEGETATION ?
YES
NO
CAN STOCK OR VEHICLES BE EXCLUDED FROM THE SITE ?
YES
NO
LIVESTOCK/VEHICLE EXCLUSION MEASURES[3]
IS THE DEGRADATION CAUSED BY GRAZING PRESSURE OR A FOOT PATH FOR STOCK OR PEOPLE ?
YES
CAN STOCK OR PEOPLE BE EXCLUDED FROM THE SITE?
YES
NO
LIVESTOCK/ HUMAN EXCLUSION MEASURES[3]
STOCK/HUMAN MANAGEMENT[4]
FOOTPATH TO BE EROSION PROOFED AND UPGRADED STRUCTURALLY[7]
ESTABLISH FORD[6] or BRIDGE[5] IF APPLICABLE
ARE THERE HEAVY VEHICLES ACCESSING THE CROSSING POINT ?
YES
NO
LIVESTOCK MANAGEMENT[4] and BRIDGE[5]
ONLY LIGHT VEHICLES AND/OR STOCK CROSSING ?
YES
LIVESTOCK/VEHICLE MANAGEMENT[4] and BRIDGE[5] or FORD[6]
Go To C
C
IF FIELD ASSESSMENT SCORE IS...
between 8 and 15 go to G
between 16 and 23 go to E
between 24 and 31 go to D
greater than 31 go to F


D
IS THERE EVIDENCE OF SOIL FALL, MAJOR RILLING or GULLYING?
NO
Go To E
YES
HAS THE RILLING or GULLYING LED TO PATCHES OF STREAM BANK BEING SCOURED OUT OR HAVING SLUMPED, LEAVING A VOID?
NO
IS THIS SITUATED AT THE LOWER BANK AND WATER'S EDGE, THE ENTIRE BANK FACE OR UPPER BANK?
JUST LOWERBANK
IS THIS A LOW ENERGY ENVIRONMENT?
YES
APPLY BRUSH MATTRESSES[10] ON THE BANK AND COCONUT FIBRE ROLL[11] AND VEGETATIVE PLANTINGS[9] AT THE TOE
NO
JUST UPPER BANK
ENTIRE BANK FACE
IS THIS A LOW TO MODERATE ENERGY ENVIRONMENT?
YES
UTILISE LIVE FASCINES[12] IN COMBINATION WITH BRUSH MATTRESSES[10] AND STONE TOE PROTECTION[13]
Go To G
BRANCH PACKING[8] WITH VEGETATIVE PLANTINGS[9]
Go To G
NO
IS THIS A HIGH ENERGY ENVIRONMENT?
YES
IS BANK SHAPING AND PLANTING[15] FEASIBLE?
YES
UNDERTAKE BANK SHAPING AND PLANTING[15], APPLY STONE TOE PROTECTION[13] AND VEGETATIVE PLANTINGS[9] AT THE TOE
NO
UTILISE BRUSH MATTRESSES[10] AND JOINT PLANTINGS[14] ON THE BANK, AND STONE TOE PROTECTION[13] WITH VEGETATIVE PLANTINGS[9] AT THE TOE
YES
ARE THESE PATCHES MORE THAN APPROXIMATELY 1m DEEP AND 1m WIDE?
NO
UTILISE BRANCH PACKING[8] WITH COMPACTED BACKFILL AND VEGETATIVE PLANTINGS[9] TO PROVIDE IMMEDIATE SOIL REINFORCEMENT
YES
ARE THE STRESSES CAUSING THE SLUMP STILL PRESENT?
NO
IS THE RILLING or GULLYING RELATIVELY SEVERE AND/OR IS THE LOCATION SUCH THAT VEGETATION IS NOT LIKELY TO RE-ESTABLISH RAPIDLY?
YES
IS THIS ONLY AT THE TOE?
YES
APPLY STONE TOE PROTECTION[13] WITH JOINT PLANTINGS[14] WHERE FEASIBLE
NO
IS RILLING DISTRIBUTED ACROSS THE ACTIVE BANK?
YES
LOWER ENERGY ENVIRONMENT
APPLY RIPRAP[16] WITH JOINT PLANTINGS[14] WHERE FEASIBLE
or
HIGH ENERGY ENVIRONMENT
APPLY MATTRESS/CELLS[17] WITH JOINT PLANTINGS[14]
NO
YES or UNCERTAIN
Go To F


E
IS THERE EVIDENCE OF SHEET EROSION, MINOR RILLING OR MINOR SOIL FALL?
YES
NO
IS THIS SITUATED AT THE LOWER BANK AND WATER'S EDGE, THE ENTIRE BANK FACE OR UPPER BANK?
JUST LOWERBANK
JUST UPPER BANK
ENTIRE BANK FACE
IS THIS A LOW ENERGY ENVIRONMENT?
YES
NO
UTILISE BRUSH MATTRESSES[10] AND POSSIBLY A COCONUT FIBRE ROLL[11] AT THE TOE
IS THIS A LOW TO MODERATE ENERGY ENVIRONMENT?
NO
YES
UTILISE LIVE FASCINES[12] IN COMBINATION WITH BRUSH MATTRESSES[10] AND STONE TOE PROTECTION[13]
Go To G
IS THERE EVIDENCE OF MAJOR RILLING OR GULLYING?
YES
NO
BRANCH PACKING[8] WITH VEGETATIVE PLANTINGS[9]
IS THIS A HIGH ENERGY ENVIRONMENT?
YES
UTILISE VEGETATED GEOGRIDS[18] OR SOIL-FILLED CELLS[19]
Go To D


F
IS THERE EVIDENCE OF EXTENSIVE SLUMPING OR MASS FAILURE?
YES
NO
IS THE BANK >3m HIGH, THE FIELD ASSESSMENT SCORE >36, OR IS A STRUCTURE IN SERIOUS JEOPARDY FROM BANK DEGRADATION?
YES
NO
IS THE BANK HEIGHT GREATER OR LESS THAN 1.5m?
>1.5m
<1.5m
IS BANK REPROFILING FEASIBLE?
YES
NO
UNDERTAKE BANK SHAPING AND PLANTING[15]
LOW RISK
HIGH RISK
APPLY RIPRAP[16] WITH JOINT PLANTINGS[14]
APPLY MATTRESS CELLS[17] WITH JOINT PLANTINGS[14]
STABILISE UPPER BANK WITH DORMANT POST PLANTINGS[21] and/or LIVE STAKES[22]
CONSULT STRUCTURAL OR CIVIL ENGINEER
IS THE SLUMPING SITUATED ON THE OUTSIDE BEND OF A MEANDER, NEAR A STRUCTURE OR IN ANY OTHER HIGH ENERGY ENVIRONMENT?
YES
NO
IS THERE EVIDENCE OF BANK SCOUR?
NO
YES
Go To D
IS THE BANK >1.5m OR IS IT IN A HIGH ENERGY OR HIGH RISK ENVIRONMENT?
YES
NO
IS IT SITUATED ALONG A SECTION OF PARALLEL FLOW OR A LOWER ENERGY ENVIRONMENT?
NO or UNCERTAIN
YES
IS BANK REPROFILING FEASIBLE?
NO
YES
IS THERE A READIER SUPPLY OF TIMBER/LOGS OR STONE/ROCK?
LOGS
STONE
ESTABLISH LIVE CRIBWALLS[23]
PUT VEGETATED GABIONS[24] IN PLACE
IS THE BANK <50cm OR IN A LOW ENERGY ENVIRONMENT OR A LOW RISK AREA?
NO
YES
CAN THE BANK BE STABILISED BY PROTECTING THE TOE ONLY?
YES
NO
UNDERTAKE BANK SHAPING AND PLANTING[15]
LOW ENERGY
HIGH ENERGY
APPLY TREE[25] or LOG, ROOTWAD AND BOULDER[20] REVETMENTS and JOINT PLANTINGS[14]
IS BANK REPROFILING FEASIBLE?
NO
YES
APPLY RIPRAP[16] WITH JOINT PLANTINGS[14] WHERE FEASIBLE
UNDERTAKE BANK SHAPING AND PLANTING[15] USING VEGETATED GEOGRIDS[18]
STABILISE UPPER BANK WITH DORMANT POST PLANTINGS[21] and/or LIVE STAKES[22]
UNDERTAKE STONE TOE PROTECTION[13]
Go To E
Go To G


G
ARE SPECIES OF ALIEN VEGETATION PRESENT?
YES
NO
WOULD REMOVING ALIEN VEGETATION POSE A RISK TO BANK STABILITY?
YES
NO
RINGBARK TREES[26] WHICH ARE FULFILLING A BANK STABILITY FUNCTION AND CLEARFELL[1] THE REST
CLEARFELL[1] ALIEN VEGETATION (IN ONE OPERATION OR IN SMALLER SEGMENTS) AND RETAIN TIMBER FOR USE IN REHABILITATION
• REPLACE IMMEDIATELY WITH INDIGENOUS SPECIES AND MAINTAIN
• THE ROOTS OF CLEAR FELLED PLANTS MUST BE RETAINED
• SOME TREES MUST BE AVAILABLE TO MAINTAIN ECOLOGICAL FUNCTIONS
• ESTABLISH FLOW STRUCTURES WHERE FLOW ENERGIES ARE TOO HIGH
IS THE WIDTH OF THE RIPARIAN ZONE AT LEAST 5m plus BANK HEIGHT FROM BANK CREST?
NO
DEMARCATE OUTER BOUNDARY
YES
EVALUATE VEGETATION[27] IN THE RIPARIAN ZONE ACCORDING TO
• OVER STOREY
• UNDER STOREY
• GROUND COVER
• MARGINAL COVER
BASED ON SITE LOCATION INTEROGATE THE VEGETATION DATABASE TO PROVIDE A SPECIES LISTING
UTILISE THE RECOMMENDED SPECIES PLANT USING THE FOLLOWING TECHNIQUES:
• LIVE STAKES[22]
• DORMANT POSTS[21]
• LIVE FASCINES[12]
• BRANCH CUTTINGS
• SEEDS
• PLUGS
• SEEDLINGS

APPENDIX C

The use of magnetic susceptibility measurements to delineate wetlands in KwaZulu-Natal, South Africa

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Abstract

Wetland delineation in South Africa is often time consuming and difficult due to the subjective nature of the soil survey method. The aim of this research was to investigate the possibility of using soil magnetic susceptibility to differentiate wetland soil from non-wetland soil, thereby enabling identification of a boundary. The initial reconnaissance work was carried out at nine sites in three areas of Kwazulu-Natal, South Africa. Magnetic susceptibility readings could be used to differentiate between the various wetland zones on a site-specific basis. This reconnaissance phase was to assess the potential of using soil magnetic susceptibility for wetland delineation and it was concluded that further investigation was warranted. A second method was designed specifically to identify the outer wetland boundary. Magnetic susceptibility readings were done on transects perpendicular to the suspected boundary, identified according to vegetation indicators, and a critical value that separates wetland from non-wetland soil was identified. A magnetic susceptibility boundary was marked according to the critical value. The actual boundary was then identified using the South African field procedure according to soil indicators. The soil data showed a similar boundary to the magnetic susceptibility critical value but a 'boundary zone' 12m in width, rather than a specific line, was identified. A final method was developed in an attempt to improve the resolution of the magnetic susceptibility boundary. A grid was laid out over a strip through the wetland including the boundary area on both sides. This was to provide accurately spaced points at which to take magnetic susceptibility readings. The critical value was identified and verified using soil indicators. The field procedure was more difficult to carry out than using the magnetic susceptibility sensor, yet both methods identified the same boundary with a resolution of approximately 3m. Although the results at

the final site proved the method to be successful, it was not suitable for use at all sites and the results were often difficult to interpret. This initial study demonstrates the potential for using magnetic susceptibility for wetland delineation in KwaZulu-Natal.

Introduction

Delineation of wetlands is necessary to enable management planning when wetlands fall within an area affected by human activities such as forestry or farming (Williams, 1990; Lyon, 1993; Mitsch and Gosselink, 1993). In South Africa, wetlands are delineated using a field procedure based on soil morphology, vegetation and landscape position (Land-Use and Wetland/Riparian Habitat Working Group, 1999; Marnewecke and Kotze, 1999). This procedure can be time consuming and is, to an extent, subjective. An alternative, or supplementary method could possibly be provided by using a magnetic susceptibility (MS) meter to differentiate wetland soils from non-wetland soils.

All substances have magnetic properties (Smith, 1999). Measurements can be made of the magnetic properties of almost any material, making them useful in a wide range of disciplines. They are particularly useful in the environmental disciplines since the measurements are rapid, simple and non-destructive and are often quicker and easier to carry out than conventional methods (Thompson et al., 1980). One of their applications is in soil science where MS signatures can be related to soil type (Mullins, 1977). The most commonly and easily measured magnetic property of soils is the magnetic susceptibility (Mullins, 1977). Volume magnetic susceptibility, K, is defined by the relation

$$\boldsymbol{K = M / H}$$

where M is the volume magnetisation (total magnetic field per unit volume) induced in a material of susceptibility, K, by an applied field (inducing magnetic field per unit volume) H. Volume susceptibility is therefore a dimensionless quantity (Mullins, 1977; Thompson and Oldfield, 1986; de Jong et al., 1998). The units used by the Bartington system are expressed as 'x 10^{-5} SI units' (Bartington Instruments, 2001).

Magnetic minerals consist largely of iron oxides. The magnetic susceptibility of soils is directly related to the concentration of magnetic minerals present, as well as their grain size and shape

(Thompson and Oldfield, 1986). Most magnetic susceptibility changes are due to variations in the concentrations and grain sizes of magnetite and maghaemite (Grimley and Vepraskas, 2000). Table 1 indicates various soil parent rocks and minerals and how they affect magnetic susceptibility.

Table 1 Parent materials, minerals and their magnetic behaviour. Constructed from Thompson & Oldfield (1986), Dearing (1999), Smith (1999).

Parent material	Minerals	Type of magnetism	Magnetic susceptibility
Igneous rocks (e.g. basalt, gabbro, granite).	Magnetite, maghaemite	Ferrimagnetic	Strong positive susceptibility
	Ilmenite, titanoheamatite, rutile	Canted antiferromagnetic	Moderate positive susceptibility
	Pseudobrookite	Paramagnetic	Weak positive susceptibility
Sedimentary rocks (e.g. red beds, limestones, ocean sediment).	Iron sulphides	Ferrimagnetic	Strong positive susceptibility
	Haematite and goethite, titanomagnetite	Canted antiferromagnetic	Moderate positive susceptibility
	Quartz and feldspars	Diamagnetic	Weak positive susceptibility
Metamorphic rocks (e.g. slate)	Haematite, ilmenite	Canted antiferromagnetic	Moderate positive susceptibility
	Pseudobrookite	Paramagnetic	Weak positive susceptibility

Waterlogged soils, such as those of wetlands, tend to have a lower iron mineral concentration since ferrimagnetic minerals are reduced and leached out of the profile (McBride, 1994). Theoretically then, wetland soils should exhibit lower magnetic susceptibilities than non-wetland soils where the ferrimagnetic minerals are in the oxidised state and less soluble.

The aim of this research was to investigate the possibility of using MS to develop a rapid wetland delineation method in order to save time when mapping wetlands over large areas. The objectives were to determine whether using MS for delineating wetlands in Kwazulu-Natal, South Africa is likely to be successful or not. If so, for which land types (geology, soils, climate, vegetation) the use of MS may be appropriate, to design a quick, user-friendly field method; and provide recommendations for further research.

Experimental

The results of a study undertaken by Grimley and Verpraskas (2000) indicated that it was possible to delineate the marshland at their site in Illinois in the United States of America using a method that involved taking surface MS readings only. Their approach was adopted for this study since it was quick and had the potential to be developed into a 'user-friendly' procedure but it was not known what results could be expected under the different conditions in South Africa. The methodology was therefore divided into two phases, a reconnaissance phase to determine whether further study was warranted and a second phase to develop and refine a protocol for using MS to delineate wetlands.

The Bartington Instruments Ltd. (Witney, Oxford, U.K.) Magnetic Susceptibility System (MS2 Meter and MS2D Sensor) was used. The MS2D sensor was used for this study since it enables quick surface volumetric MS measurements . The unit is portable and simple to operate, making it ideal for this study.

Initial methodology to test viability

The broad study area consisted of the province of KwaZulu-Natal. The geology of the province consists of a combination of sedimentary, igneous and metamorphic rocks providing a varied range of parent materials. Commonly occurring parent materials and their dominant mineral compositions are as follows : shale (quartz, micas), granite (feldspars, quartz), coastal plain sediment (quartz, calcite), sandstone (quartz), basalt (feldspars, pyroxene), dolerite (feldspar, pyroxene), tillite (quartz, feldspar, other rock fragments) and crystalline schist (mica, chlorite) (Holmes 1978; King 1972). KwaZulu-Natal has been divided into land types (Soil and Irrigation Research Institute and Department of Agriculture and Water Supply, 1998) based on terrain units, defined as 'any part of the land surface with homogenous form and slope', pedosystems, defined as 'land over which terrain form and soil pattern each display a marked degree of uniformity' and climate zones. Data have been collected for each land type based on the geology and soils. A study has also been done by Fitzpatrick (1978) entitled 'Occurrence and properties of iron and titanium oxides in soils along the Eastern Seaboard of South Africa'. Since iron oxides are important contributors to the magnetic properties of soils, this study provided much insight as to where MS measurements were likely to be more successful in the province. Based on the information above, as well as a generalised soil map for the province, three regions were selected, differing in parent material and soil type.

Coastal wetland

The sites in this region were situated along the northern KwaZulu-Natal coast, in the vicinity of St Lucia / Sodwana Bay. The geology in the area consists of Cainozoic and Recent sediments (sea-bed sandstones and mudstones, limestones, loose sand) and Cretaceous sediments (also sandstones, some enriched with minerals brought downstream by rejuvenated rivers) (King 1972). Fitzpatrick's (1978) generalized soil map shows that the soil types in this area consist of grey and red sands. The study sites consisted of grey sands. Fitzpatrick (1978) compiled a map showing the distribution and abundance of maghaemitic concretions in KwaZulu-Natal. Since maghaemite is one of the major contributors to the magnetic component of soils, this map gives an indication of the magnetic-mineral content of the soil. This map indicates that the distribution and abundance of maghaemitic concretions in this Northern coastal region is absent to very few.

Floodplain wetland, silt deposit (Pongola river floodplain)

The parent material in this area is made up of the Ecca, Beaufort and Dwyka Series and consist of shale, sandstone, granites, gneisses, mica and kyanite schists, lavas, hornfels and quartzite. It forms a sedimentary mixture deposited by ancient glaciers (King, 1972). The soils are mainly weakly developed (lithocutanic B horizons), plinthic and some red and black clays and duplex soils (Fitzpatrick, 1978). As the Pongola river gets closer to the sea, it flows through black clays, red structured clays and duplex soils (Fitzpatrick, 1978). The distribution and abundance of maghaemite concretions is described as few (1-3%) and absent to very few (Fitzpatrick, 1978).

Inland site, away from floodplains (Drakensberg / Natal Midlands)

The Ecca and Beaufort series dominate in this area with the predominant geology consisting of shale, sandstone and dolerite intrusions (King, 1972). The soil types are red apedal, mesotrophic clays to yellow apedal loams; yellow and red apedal, freely drained, dystrophic soils; yellow and grey hydromorphic, mesotrophic sands and loams; some red clays and duplex soils (Fitzpatrick, 1978). The maghaemite abundance map shows that concretions are common (>5%).

Table 2 is a summary of all the sites studied in the initial fieldwork. The method for collecting data at these sites was not rigid, much time was spent experimenting with the MS meter and various ways of trying to detect boundaries. At all the sites the permanently wet, seasonally wet and temporarily wet zones were identified (approximately) by changes in vegetation. MS readings and corresponding soil samples were taken on transects through these zones to identify any useful trends in the MS readings and to distinguish wetland soil from non-wetland soil using the field procedure (Land-Use and Riparian/Wetland Habitat Working Group, 1999). All grass and debris was cleared from the soil surface before the MS readings were taken using the MS2D sensor. The soil samples were taken at depths of 0-20cm and 20-40cm and sealed in plastic bags for further analysis. The colour of each sample was recorded using a Munsell colour book. The presence of mottles was also noted, as well as their chroma (high or low). The soil form was identified if possible according to the South African Soil Classification System (Soil Classification Working Group, 1991). The colour in the wet state was also recorded. Each sample was air dried and the colour in the dry state recorded. Table 3 indicates the criteria used to classify the soil samples, together with the ‘Wetland/Riparian Habitats : Practical Field Procedure for Identification and Delineation. Version 1.2.’ (Land -Use and Wetland/Riparian Habitat Working Group, 1999).

Table 2 Reconnaissance field work in Pongola, Sodwana and the Natal Midlands.

Area	**Site No.**	**Site Name**	**Location**	**Site Type**	**Parent Material**	**MS[1] only**	**Samples[2], MS**	**Level[3], MS, No samples**	**Level, MS, Samples**
Pongola	1	Bubhe	S26°59.812’ E32°18.041’	Floodplain	Silt deposit, sedimentary mixture	1 (one bank) (MS2F)	1[4]	0	0
	2	Sokhunti	S27°01.447’ E32°17.845’	Floodplain	Silt, sand	2 (opp banks)	2	0	0
	3	Nomaneni	S26°59.218’ E32°16.662’	Floodplain	Silt, rhyolite ridge	none	2	0	0
Sodwana	4	Mkuze	S27°35.061’ E32°28.512’	Coastal	Regic sand	1 (one side)	2	1	0
	5	Yengweni	S27°37.913’ E32°25.924’	Coastal	Regic sand	1	1 (two tongues)	0	0
Natal Midlands	6	Highmoor	S29°19.352’ E29°36.904’	Inland	Basalt Basalt	1 1	0 0	0 0	0 0

7	Oribi	S29°39.122’ E30°24.340’	Inland	Shale	none	2	0	0
8	Hesketh	S29°39.166’ E30°24.323’	Inland	Shale	none	1	0	0
9	Shafton	S29°27.129’ E30°14.768’	Inland	Dolerite	none	1	0	1

[1] MS refers to magnetic susceptibility readings taken along a transect perpendicular to the water’s edge at intervals of 1 or 2m

[2] Soil samples were taken along the similar transects, often the same transects, to correspond with MS readings in the various wetland zones.

[3] A dumpy level was used to obtain elevation readings at 1m intervals on certain transects.

[4] The numbers indicate the number of transects sampled in the same way at each site.

Table 3 A provisional three-class system for determining the degree of wetness of wetland soils. After Kotze et al. (1996).

Soil depth (mm)		**Degree of wetness**	
	Temporary	Seasonal	Permanent/semi-permanent
0-100	Matrix chroma 0-3 Mottles few/nil Low/intermediate OC[1]	Matrix chroma: 0-2 Mottles common Intermediate OC	Matrix chroma: 0-1 Mottles nil/few High OC
300-400	Mottles few Matrix chroma: 0-2	Mottles common/many Matrix chroma: 0-1	Mottles nil/few Matrix chroma: 0-1

[1] High OC : soil organic carbon levels are greater than 5%, often exceeding 10%
Low OC : soil organic carbon levels are less than 2%

Transect and grid methods

The second ‘transect method’ involved a closer analysis of the boundary area only, rather than all the wetland zones. The fieldwork was carried out near the town of Mooi River in the Natal Midlands. The first step involved a study of the slope and grasses. The wetland was situated in the catchment of a dam on a small floodplain bounded by gentle slopes. The upper part of the slopes were under forestry and the trees had been recently harvested. The wetland zones were identified by looking at changes in vegetation and specific grass species (Land-Use and Wetland/Riparian Habitat Working Group 1999).

The MS boundary was located using transects as follows : Four transects (Fig. 1 T1-T4) were done from the non-wetland area across the temporary zone into the seasonal zone to try and identify if / where the MS readings decreased to below a certain level. A tape measure was used to mark the transects (approximately 35m each) and MS readings were done at 1m intervals. On completion of each transect, a point on the tape was identified where the boundary was thought to be (where the readings dropped suddenly and remained low). A marker was left at the spot. Completing the four transects left four markers along the suspected boundary (curved line). These four markers were then joined using the measuring tape to make an 80m marker along the suspected boundary.

Two more MS transects (T5 and T6, Fig. 1) were then done parallel to the tape on either side, at a distance of approximately 2m from it to verify it's boundary position. All the values along the transect on the non-wetland side needed to be above the critical value and all the readings on the wetland side needed to be below the critical value. Soil analysis was then done at 6 points, three on either side of the boundary (Fig. 2, points 1-6). Criteria used to identify whether the soil could be classified as wetland or not included soil form, soil colour and soil wetness factor according to the Field Guide for Wetland Identification and Delineation (Land-Use and Wetland/Riparian Habitat Working Group, 1999). Problems were experienced with this method, mainly due to the variability in readings given by the MS meter. A revised method was therefore planned to try and improve the resolution of the MS boundary.

An undisturbed site at Midmar Dam in the Natal Midlands was selected for the grid method. Sisal string was used to construct a 2m square grid which ran 100m parallel with the boundary zone and was 50m wide. MS readings were taken at the intersections of the string i.e., at each corner of the squares but due to the poor MS results, related to the parent material, a new site was selected at Oribi airfield in Pietermaritzburg. This was a smaller wetland so a long narrower grid was constructed through it, to include the boundaries on both sides. The grid was constructed in the same way as the Midmar one, it measured 84m in length and 16m across. MS readings were taken at the corners of the squares. The MS grid was studied to locate the suspected wetland boundaries (by subjectively looking for a critical value on the grid) which were then marked on the ground. The field procedure was followed to identify whether the MS boundary coincided with the soil indicators. Six auger points were taken, three on each side of each boundary within the first block away from it i.e., within a range of 2m either side of the MS boundary. The grass species were also noted. The MS grid was analysed statistically by constructing a histogram of all the values. This was to confirm / check the critical value subjectively selected in the field (Grimley and Verpraskas, 2000).

Results

Initial methodology

Only the results from the most interesting and representative sites in each area are presented. Fig. 3 and Fig. 4 show two MS transects studied on opposite sides of the wetland at site 2 (Sokhunti). Zones were selected according to vegetation changes. In Fig. 3 the MS readings increased with distance from the water. Transect 2 showed a different trend to transect 1 with the MS values peaking at the water's edge, decreasing, increasing again and then dropping once out of the temporary zone.

Fig. 5 shows how the readings increased in the temporary zones at site 4 (Mkuzi). The MS readings were lower than those at Pongola but a trend could still be observed. The trough of low readings indicates the permanently wet zone. Readings then increase in the seasonal and temporary zones and drop again once outside the wetland.

The readings at Yengweni (site 5, Fig. 6) showed 3 peaks with low MS troughs between them. The transect was done on a flat section of bank, it was difficult to identify the wetland zones. Fig. 7 shows the MS readings done on a transect through a wetland at Highmoor nature reserve (site 6) in the Drakensburg mountains. The readings are erratic in the temporary and seasonal zones, showing a constant low range of values only in the permanent zone.

Fig. 8 shows site 7 (Oribi), a wetland transect studied in the same region as site 6 but at a lower altitude. The readings increased from the edge of the permanent zone and it was possible to (subjectively) detect a critical MS value that corresponded with vegetation and soil indicators, indicating the boundary of the wetland.

Transect and grid methods

The MS readings on transects 1 to 4 of the transect method, used to identify the critical value, are represented in Fig. 9. Transects 5 and 6 were used to verify the critical value by showing MS readings higher than 100 x 10^{-5} SI units on the non-wetland side and lower than 100 x 10^{-5} SI units on the wetland side but the readings showed large variations within a distance of 1m, not verifying the value conclusively. Table 4 includes the soil data for each point. The location of the point numbers is visible in Fig. 2.

Table 4 Soil data taken to verify the MS boundary identified at the Mooi River site.

Point number	Signs of wetness, chroma at 50cm depth	Soil form	MS reading x 10^{-5} SI units	Wetland / non-wetland according to field procedure
1	None, chroma 4	Hutton	215	non-wetland
2	Few high chroma mottles, 3 (soil was wet)	Sepane	59	wetland, difficult decision though
3	None within 50cm, mottles at 1m, chroma 3	Sepane	283	non-wetland
4	Mottles, matrix chroma 2	Sepane	43	wetland
5	None within 50cm	Pinedene	277	non-wetland
6	Mottles, chroma 2 at 50cm	Sepane	47	wetland

The first attempt at the final methodology was undertaken at a site at Midmar Dam in Howick. The MS readings showed very little variability and no boundary could be detected. A second site was therefore selected at Oribi airfield in Pietermaritzburg. As estimated in the field, the histogram in Fig. 10 shows the critical value can be taken at approximately MS 250. This value corresponds with the mean of the wetland soil MS values plus three standard deviations, a calculated value of 252 (Grimley and Verpraskas 2000).

The soil data taken on either side of the MS boundary to verify it is included in Table 5. Points 1, 3, 5, 7, 9 and 11 were taken on the non-wetland side of the MS boundaries on both sides of the wetland. The even-numbered points were taken on the wetland sides. Not all the points verified the MS boundary, resulting in a resolution of approximately 3m (a boundary width of 3m).

Table 5 Soil data taken to verify the MS boundary identified at the Oribi grid site.

Point number	Signs of wetness, chroma at 50cm depth	Soil form	Grasses	Wetland / non-wetland according to field procedure
1	None, chroma 4	Hutton	*Themeda triandra*	Non-wetland
2	Mottles, chroma 2	Sepane	*Setaria sphacelata*	Wetland
3	None, chroma 3	Hutton	*Themeda triandra*	Non-wetland
4	None, chroma 2	Deep Hutton	*Themeda/Setaria*	Non-wetland
5	Mottles, chroma 2	Sepane	*Setaria sphacelata*	Wetland
6	None, chroma 4	Hutton	*Themeda triandra*	Non-wetland
7	None, chroma 3	Mispah, 40cm deep	*Themeda triandra*	Non-wetland
8	Mottles?[1], chroma 2	Mispah	*Themeda/Setaria*	Wetland
9	None, chroma 3	Mispah, 40cm deep	*Themeda/Setaria*	Non-wetland
10	Mottles?, chroma 2	Mispah	*Themeda/Setaria*	Wetland
11	None, chroma 3	Mispah, 40cm deep	*Themeda/Setaria*	Non-wetland
12	Mottles?, chroma 2	Mispah	*Themeda/Setaria*	Wetland

[1]The nature of the horizon made it difficult to identify mottles, if present.

Discussion

Initial fieldwork

The initial fieldwork showed a variety of results. The work at Pongola, the Kwazulu-Natal North coast and the Midlands showed that, for the wetland sites studied, MS values were usually lower at the water's edge than outside the temporary zone. It was determined that grass cover between the MS sensor and the soil decreases the sensitivity to the soil MS, a good contact between the sensor and the soil is required. It was not possible to determine a critical boundary value that could be used at all sites in an area since conditions at the sites varied causing MS values in different ranges for the same area. Sokhunti (Fig. 3 and 4) showed a different trend on opposite sides of the same wetland. This was due to different conditions on each side. Fig. 4 represents a slope with dark coloured, well structured soil at the base and light, sandy textured soil at the crest, probably lower in iron due to leaching and the movement of dissolved solids downslope. Soil verification of the MS wetland zone boundaries was always successful but too much emphasis was placed on the zones within the wetlands, rather than the outermost wetland boundary.

It is difficult to make general conclusions about the Pongola floodplain since the sites showed a variety of MS ranges and different trends. This was perhaps due to the fact that the floodplain consists of a mixture of parent materials, as well as much alluvium accumulated over years of deposit by the river of its various loads from upstream. However, the MS trends did coincide with the soil conditions at every site. When evidence of iron was present in the form of red streaks and mottles, the readings were higher than when the soil was sandier and obviously lower in iron, although this is a dangerous assumption to make since no soil testing was done to verify whether the mottles and streaks did indicate a higher iron content than that of the grey sands.

At Mkuze (site 4) wetland, the lowest values were obtained in the permanent zone due to the constant anaerobic conditions. These conditions cause much of the iron to become soluble and it is leached out of the profile. MS values increase in the seasonal and temporary zones due to periodic wetting and drying. Low readings were once again found outside the wetland zone due to the assumed low iron content of the sand. The in-zone variability is explained by the nature of the MS meter. The sensitivity (of the detection of the soil MS) decreases when other substances are present. If there is more organic matter (for example a thick stem) in the topsoil at one point than the point next to it, the reading will be lower. If one patch of soil is better aerated than another, more iron will be oxidized and held in the profile for detection. These variations existed at Mkuze but usually remained within the zone critical values.

At this point, it is important to mention that although reasons can be given for the variations observed in the MS readings, it is perhaps not always necessary to describe every fluctuation. The variable nature of the soil surfaces studied, together with unknown and unstudied reasons for fluctuations in the instrument mean that the variations cannot always be explained. This study forms the very first research into the use of magnetic susceptibility for rapid wetland delineation in South Africa and introduces many unknown factors that need to be investigated further before conclusions can be drawn. Much of this discussion, for example about the Mkuze site, is in the form of suggestions and ideas, rather than concrete reasons.

The MS readings shown in Fig. 6 (Yengweni wetland, site 5) are particularly interesting. The terrain was flat and it was difficult to determine the zone boundaries by looking at the vegetation. Peaks and troughs were recorded, perhaps suggesting that the water level had risen to different points in previous years, influencing the iron content of the soil at these points. This idea was not tested further but could form a study to investigate whether MS can be used to detect previous boundaries, especially in the case of disturbed, relict or altered wetlands.

The results obtained at Highmoor in the Drakensberg (site 6, Fig. 7) can possibly be explained by the fact that the site was situated in a mountain range where steep slopes and windy conditions result in thin soils and much exposed rock. The rock type was basalt, high in iron minerals, producing MS readings up to 400 x 10^{-5} SI units. The uneven surface resulted in some readings being of rock alone, while others represented a thin patch of soil, because the sensor only detects iron in the top 18cm of the soil. These varying readings makes it impossible to detect a boundary between the temporary and non-wetland soil, the permanent zone could be detected because of it's landscape position, being in a basin the soil was deeper and allowed for more consistent MS readings.

The site at Oribi (site 7, Fig. 8) had been recently burnt. It was impossible to assess the effect of the burning since a similar, unburnt site was not available for study in the same area. Studying the same site over a number of years, when burnt and not burnt could provide useful guidelines as to how to interpret MS data collected at burnt wetland sites.

The results obtained in the Natal Midlands were of mixed success. Highmoor is an example of where the MS method is unlikely to be useful while Oribi showed more promise. Northern Kwazulu-Natal showed better results than were expected and readings were in a similar range at all the sites in this area. The results on the Pongola floodplain showed that the method was successful, but like the Midlands, the range of readings and critical values were site-specific.

Transect method

The transect method carried out at Mooi River indicated that MS can be used to detect the boundary of the temporary zone, but not with great precision. Fig. 9 represents the values on T1 to T4 (Fig. 2) and shows how the critical value was selected : subjectively by choosing a value that separated the values into two major groups. It would have been more accurate to construct a histogram as was done at the final site. Table 4 indicates three different soil types within the limited study area. This probably also contributed to the variability in the MS readings. A variety of soil forming factors acting at different rates influence the iron mineral content in localized patches. Difficulty was experienced when carrying out the Field Procedure (Land-Use and Wetland/Riparian Habitat Working Group, 1999), as was experienced in the grid method. It was found that a 'buffer' of about 6m was required on either side of the MS boundary in order to get successful soil verification. This meant that the MS method was only accurate to a resolution of about 12m. Previous experience with the instrument indicated that this was not the case, a resolution of 2-3 metres was suspected but not proven.

The variability of MS readings at this site was problematic. Tree stumps, holes and animal activity (termites and duiker) all influenced the readings. An experienced user would be able to interpret the variation but a new user would probably not be able to detect the boundary. It was clear that the MS delineation did work at this site but the results were still not conclusive enough. The variation in MS readings needed to be represented more clearly and interpreted and the MS boundary needed to be determined more exactly, and proven. This led to the development of the grid method.

Grid method

The grid method at Midmar was not successful due to the presence of a plinthite (a concentration of iron and manganese nodules) layer near the surface, within the detection range of the sensor. This explained why it did not work at all and served to improve the method, it should always be preceded by a reconnaissance soil survey and decision as to whether the nature of the surface soil is likely to allow the detection of an MS boundary.

The grid method undertaken at the final site near Oribi airfield in the KwaZulu-Natal Midlands gave an MS representation of a strip through a wetland, showing how the MS values vary over 2m intervals from the higher lying soil out of the wetland zones, through the wetland and up the opposite slope. The MS critical value was selected subjectively and then checked using a histogram (Fig. 10), in the same manner of that of Grimley and Verpraskas (2000). This statistical method is fairly quick and simple and would be a useful check at sites where the critical value is difficult to detect visually.

Using the field procedure to verify the MS boundary was successful but difficulties were experienced with it. Since the soil was wet, it was difficult to identify the chroma that, according to the field procedure, should be identified on dry soil. The horizon type also sometimes made it difficult to identify signs of wetness. In a shallow Mispah soil, as was found at Oribi, weathering rock fragments and the wet conditions made it difficult to identify mottling. It was noted that the field procedure took more than twice as long to carry out than using the MS meter, even though they both identified the same boundary line with a resolution of about 3m in width.

Although this method proved that soil MS can be used to detect wetland boundaries, it was only carried out at one site. Variation between all the sites studied showed that a large amount of field work needs to be conducted in order to devise a general method, and set of guidelines, that can be applied at any site in KwaZulu-Natal.

Problems and limitations

A number of problems were experienced when testing the method, the first being the fact that the MS2D sensor only detects magnetic minerals in the top 268.7cm^2, or to a depth of approximately 18cm of the soil (Bartington Instruments 2001). This is problematic since the field method for detecting wetland boundaries requires that signs of wetness be visible within 50cm for a wetland soil to be classified. Although the field soil analysis did verify the MS boundaries in most cases, it was not always verified and was often difficult to relate the soil wetland boundary to the MS boundary. In some cases they coincided almost exactly (grid method at Oribi) while in others they were positioned three or more metres apart (transect method at Mooi River). The reason for this is difficult to explain at this stage of the research. Perhaps it is due to the fact that the sensor does not detect iron below 18cm in the profile.

Evidence in this study shows that using MS to delineate wetlands was successful at some sites so the answer to getting more consistent and accurate results may lie in extensive study of the distribution of iron in soil profiles and how the iron content in top 18cm of a profile relates to the iron content at 50cm. Another solution could be the design of a different method to take MS measurements deeper in the profile or the design of a sensor that would enable quick measurements at 50cm depths.

The success of the method depends on the conditions at each individual site. Even if a general critical value can be determined for a parent material, disturbed conditions such as at the Mooi River site, can make interpreting the readings difficult. Iron-rich rock or nodules and concretions, such as at Highmoor and Midmar, make the method completely unsuitable. It is therefore essential that a quick soil survey (three or four auger points along a transect across the suspected boundary) be done before the MS work is begun.

The MS meter itself is limited to about 2 hours of continuous reading time in the field before it needs to be charged (it has a car charger for field work), this is not a major limitation in most cases but the delineation of a large wetland might require a 30min break to charge the meter. At this stage in the research, only and experienced user would be able to carry out a MS delineation. Variations in MS readings can be difficult to interpret if the user does not have a full understanding of what the sensor is detecting. This limitation should be overcome with further research. The development of a specific protocol and MS guidelines for a range of sites would make the method accessible to users with a more limited background/knowledge in wetland delineation.

Problems were experienced with the field procedure for delineating wetlands (Land-Use and Wetland/Riparian Habitat Working Group 1999). Difficulty was experienced with identifying soil colours when the soil was wet and conditions were cloudy. Signs of wetness such as mottling were sometimes difficult to identify in horizons that contained rock fragments. Augering to a depth of 50cm at each point was time-consuming. The method is a subjective one, using a combination of this method and magnetic susceptibility readings reduces the time taken to delineate a wetland and provides a more accurate boundary.

A possible limitation to this study as a whole is the fact a large number of widely varying sites were studied. The initial intention was to provide different conditions under which to test the idea but getting such a varied range of results made it difficult to assess if the use of MS readings to delineate wetlands was generally successful or not. It was successful only at certain sites and it is difficult to know whether these results are repeatable without doing extensive fieldwork at a number of similar sites. A more useful approach would have been to select one area only and study a number of similar sites in more detail. This would have given a better indication of the general potential of the method before it was tried under different conditions.

Conclusions

Three objectives were outlined with the first being to test whether magnetic susceptibility (MS) is a viable option for delineating wetlands in Kwazulu-Natal, South Africa or not. The initial fieldwork showed that using soil MS to delineate wetlands was a viable option that would warrant further investigation.

The second objective was to determine for which conditions the MS delineation procedure is likely to be successful. This objective was partially fulfilled in that twelve different sites were studied with mixed results. The method could be used in all three of the major areas studied but was limited by specific site conditions. It is not suitable for use in areas where a plinthite layer is present in the upper 18cm of the profile. It is also not suitable for use in areas where the soil is thin (less than 18cm depth) and the surface is dominated by exposed rocks.

Difficulty was experienced when using MS to delineate wetlands in disturbed areas. Most wetlands are situated in forests and farmlands are often not in their natural state with trees or crops planted within their boundaries. Soil surfaces disturbed by vehicles, tree stumps, cattle and crop trash made interpreting the MS values difficult. This is a problem that needs further research since most wetlands that need to be delineated are disturbed. Undisturbed sites need to be selected for researching the method but consideration needs to be given to the effect of human and animal activity for a practical MS delineation procedure to be developed.

The third objective was to design a quick, user-friendly field method to delineate wetlands in KwaZulu-Natal using soil MS. The results were too variable between sites to draw general conclusions and too few sites were studied. A detailed study of different areas needs to be undertaken before specific MS guidelines can be drawn up. Problems with the method still need to be addressed and a method would need to be rigorously tested. Tables 6 and 7 outline the beginning of a field protocol.

Table 6 Guidelines for the operation of the MS meter and sensors for wetland delineation in KwaZulu-Natal.

Operation of the MS meter
• Use the MS2D sensor for quick surface measurements • Allow the meter to warm up for a few minutes before recording data. Check the consistency of the readings by doing triplicate readings at the same point. Drift sometimes occurs in the first 5min of use or if it is not fully charged. • Clear all grass and debris from the soil surface, obtain good contact between the sensor and the soil surface • Ensure that the meter is charged regularly (30mins for every 2hrs use) to avoid erratic, incorrect readings. • Do a blank reading (hold the sensor at least 30cm away from any object) between every soil reading to obtain a zero reading.

Table 7 Guidelines for determining whether a site is suitable for the use of MS or not and the delineation procedure.

Site selection
• Find out what the parent material is by observing rocks at the surface or excavations, unusually high or low readings could be explained by the rock type. • Investigate the soil depth using an auger, if the soil depth is less than 20cm the MS method is not likely to be successful • Identify the soil form, if an iron-rich subsoil lies close to the surface, the method is not likely to work. • Study the vegetation and identify the various wetland vegetation zones, the wetland boundary is most likely to be where the vegetation changes outside the temporary zone. • Select at least two transects from the water's edge out of the wetland to identify the trend in values and a critical boundary value. • Verify the critical value using soil analysis on at least one transect to rule out any MS abnormalities with the critical value (like buried boulders or rusted cans).

Recommendations for future research

The following list provides specific topics that need expansion.

I. A specific study of the top 50cm of soil profiles (including wetland soil), investigating how the iron content of the top 18cm relates to the iron content further down. This would provide some insight into how representative of the soil profile the MS2D sensor readings are. It could then be determined if using the sensor at the surface is the most accurate way of carrying out this method, perhaps a new sensor needs to be designed.

II. Another specific study would involve investigation of the chemical processes at the junction between the water (permanent zone) and the seasonal zone. An MS peak at this point was observed at almost all the sites. Sometimes mottles and streaks of iron were observed in the surface soil, studying the iron reactions could explain in more detail how and why peaks such as this occur.

III. A quick, user friendly method needs to be developed and tested. Initially it would involve a combination of MS readings and soil verification techniques. This method can be updated and improved as more areas are studied.

IV. The results of this study need to be used to divide KwaZulu-Natal (and ultimately South Africa) into MS ranges to be expected in smaller, more uniform, land-type areas. This grouping has already been done by Camp (2000) in the form of Bioresource Units (BRU) and Bioresource Groups (BRG). These were not used in this study since it was not certain at the outset whether the MS readings would be useful for wetland delineation or not. Once the method has been proven conclusively work can been done in each BRG to determine critical values for particular sets of conditions in Kwa-Zulu-Natal.

V. Another possible application of the MS method is the detection of previous wetland boundaries. Yengweni wetland on the KwaZulu-Natal north coast showed possible previous years' floodlines. This type of study would potentially be able to identify the original boundaries of disturbed or drained wetlands. This could be a useful tool in wetland rehabilitation.

VI. The work in this project focused only on naturally occurring wetlands. It would be useful to conduct a similar study on man-made wetlands. Artificial wetlands are increasingly being used for water purification and flood attenuation and also need to be protected. Grimley and Verpraskas (2000) did not get successful results at an artificial wetland but since large variations are likely to exist between materials used, and the age of the wetlands will vary, certain sites might produce successful results.

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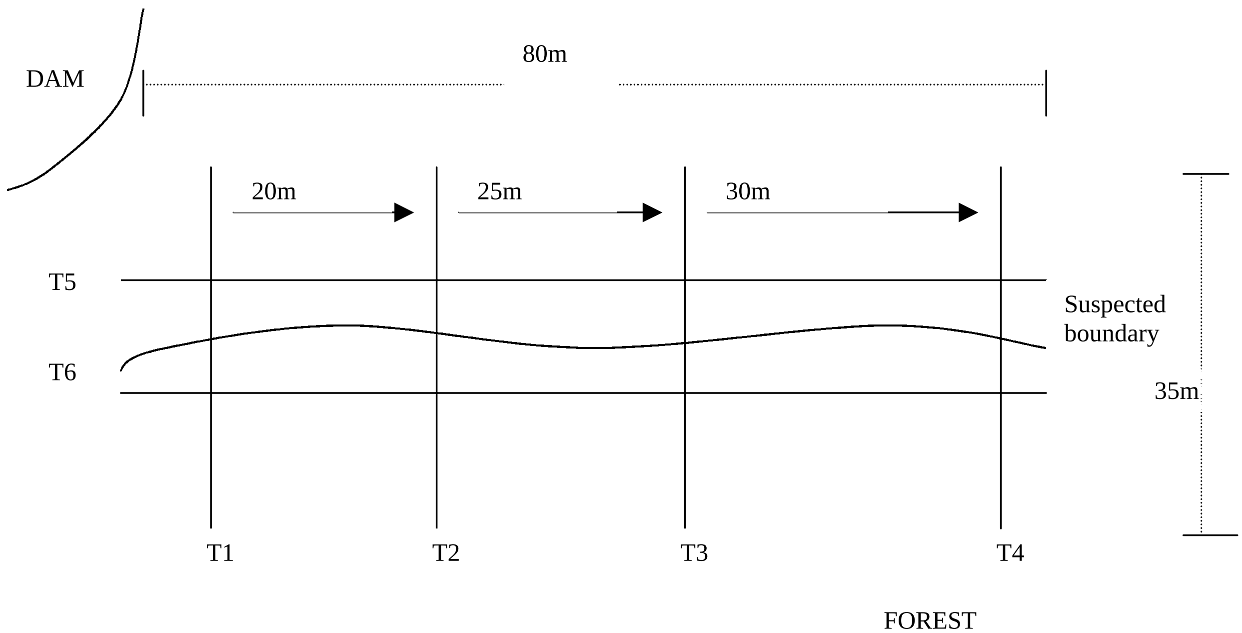

Figure 1. Transects studied near Mooi River, transect method.

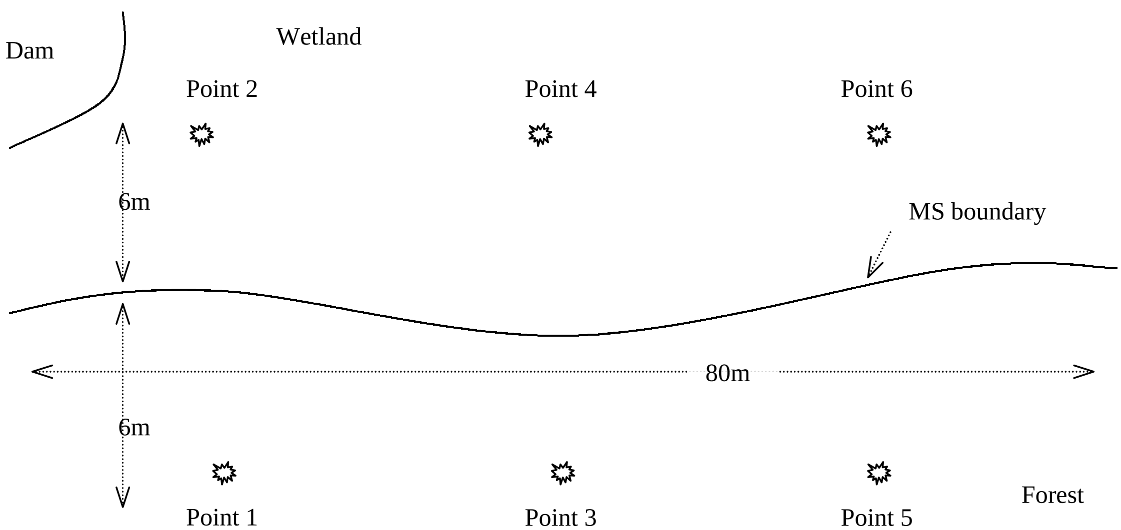

Figure 2. Points where field soil analysis was done to verify the MS boundary (transect method).

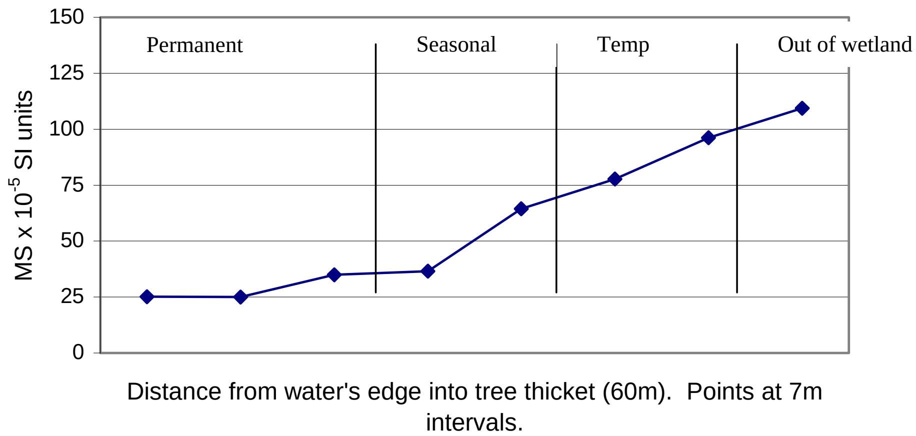

Figure 3 Sokhunti Pan transect 1.

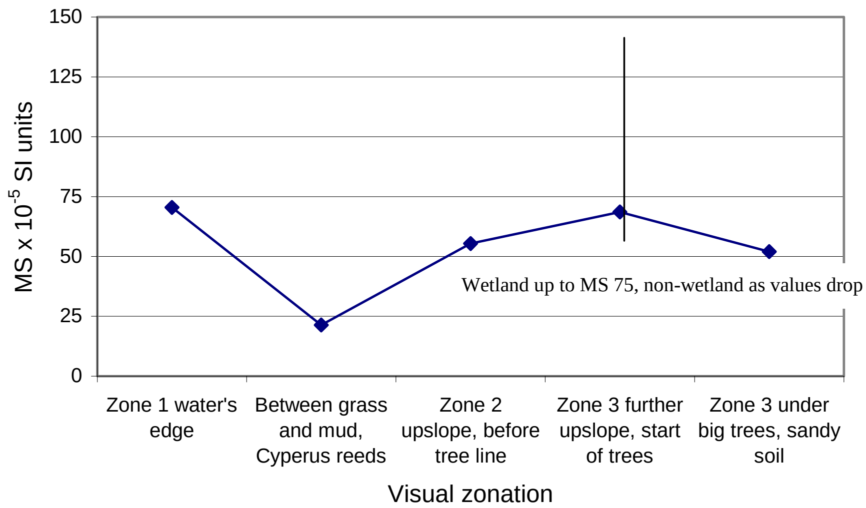

Figure 4 Sokhunte Pan transect 2

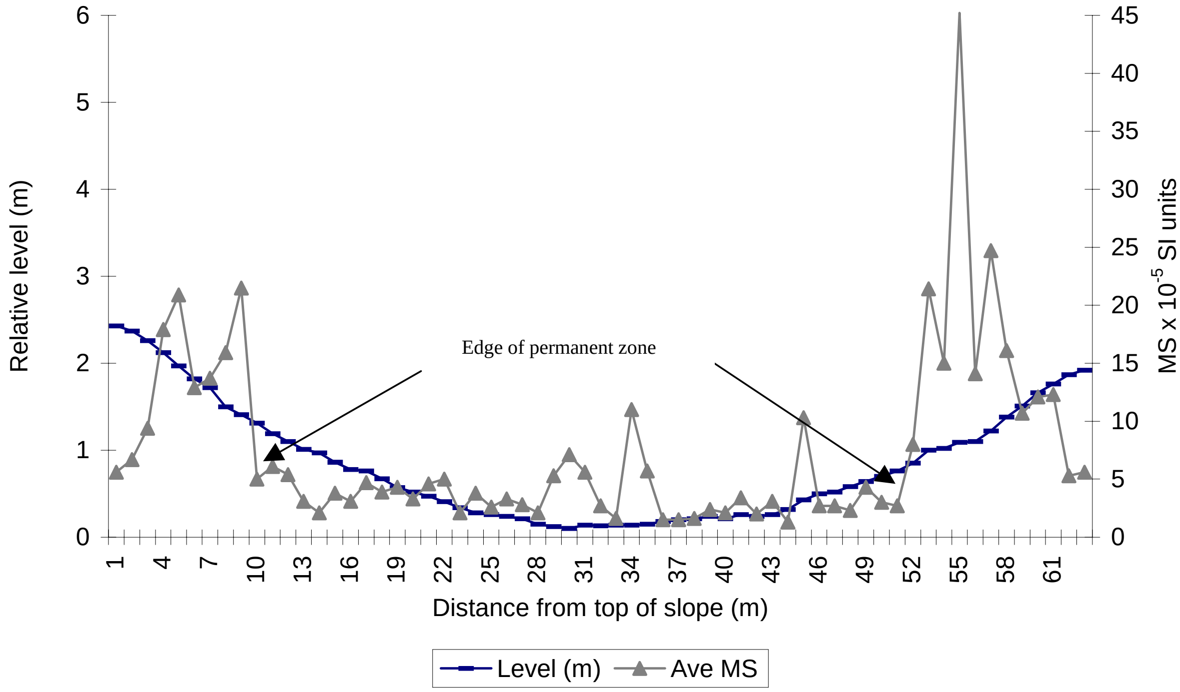

Figure 5 Mkuze wetland transect showing relative levels and their corresponding average MS readings.

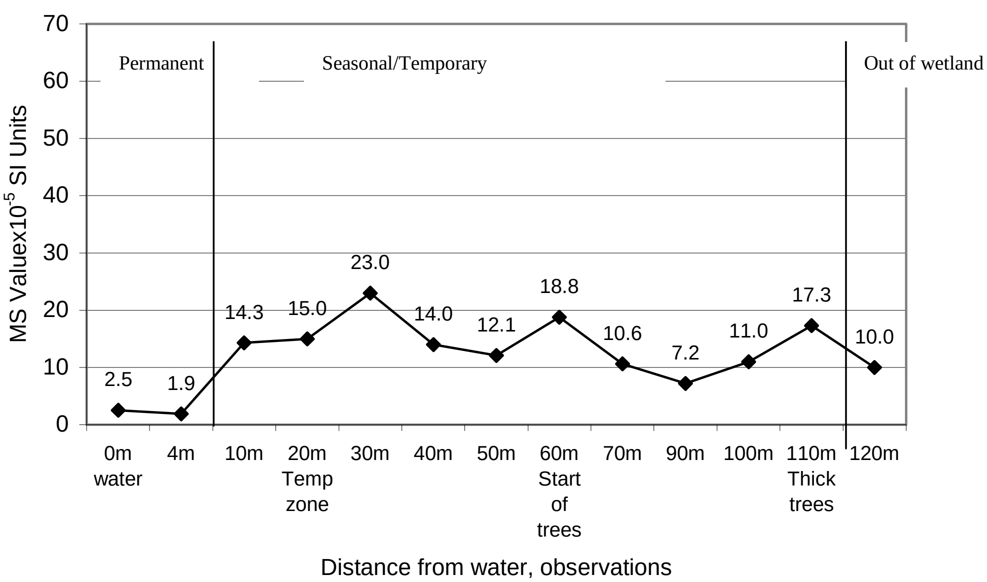

Figure 6 Yengweni wetland transect from the water's edge into dense trees.

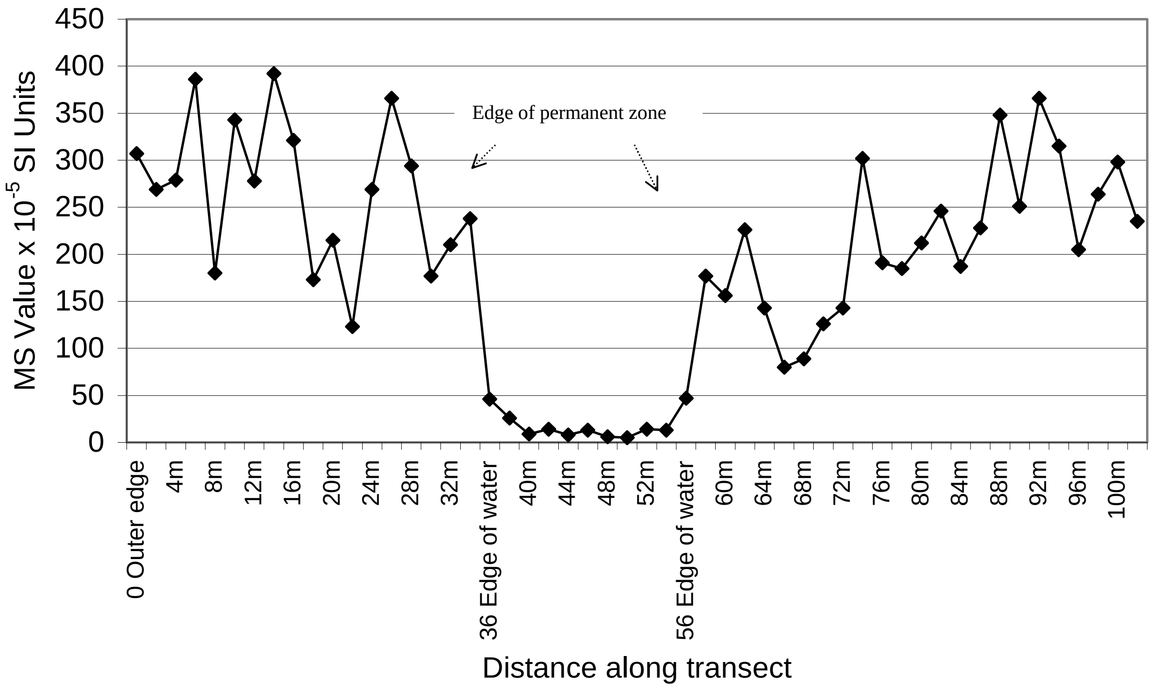

Figure 7 Highmoor wetland site.

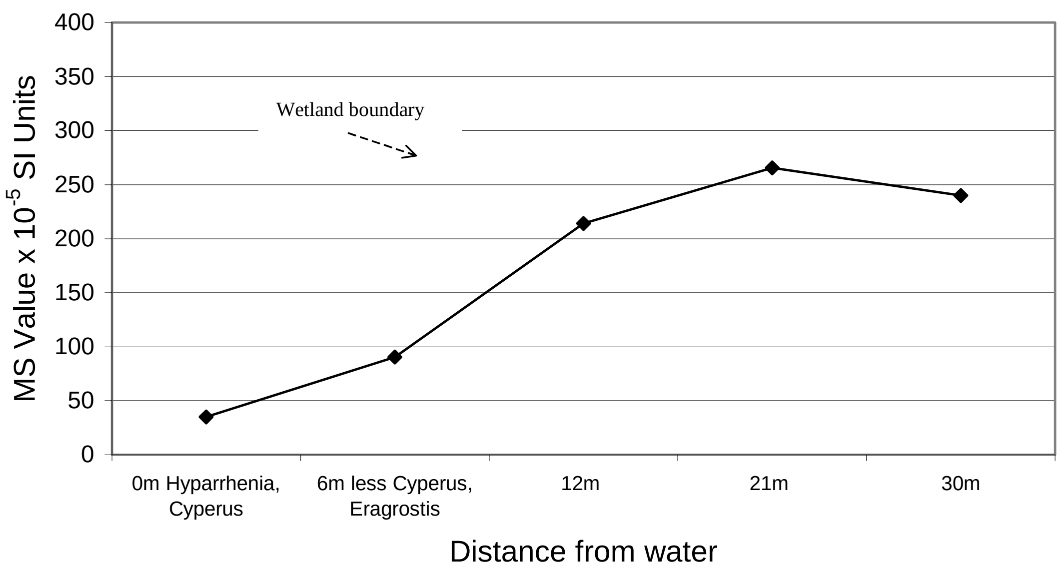

Figure 8 Oribi wetland showing transect 1

APPENDIX D

THE USE OF RIPARIAN BUFFER ZONES FOR THE ATTENUATION OF NITRATE IN AGRICULTURAL LANDSCAPES

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Abstract

The focus of this research is the use of riparian buffer zones to manage nitrate pollution of water resources. Riparian buffer zones are recognised globally for their function in water quality amelioration. Despite the growing literature, there is little consensus on how to design, assess and manage these riparian buffer zones specifically for nitrate attenuation.

Two key processes responsible for immobilising and/or removing nitrate from surface and subsurface flows are generally recognised in international literature, namely: vegetative uptake and denitrification. This research suggests that certain riparian characteristics are most responsible for enhancing the key mechanisms. Riparian buffer zones that have shallow lateral subsurface or uniform surface water delivery pathways, vegetation of close structure and composition, high organic matter in the soils and fluctuating soil surface saturation rates are likely to have the most significant nitrate attenuation efficiencies.

The research proposes that these similarities can be used to both assess the current nitrate attenuation potential of a riparian landscape, and to size a riparian buffer zone specifically to attenuate more than 75% of the nitrate within the environment. A set of proposed guidelines based on the findings of the research attempt to illustrate how riparian pollution control recommendations can be achieved.

Introduction

Nitrate is one of the most commonly recognised agricultural-related pollutants of water resources, which is usually applied to croplands as fertilizer. It is implicated as one of the main compounds contributing to excessive eutrophication of many South African rivers and dams (Dallas & Day 1993; Giliomee 1998; O'Keeffe *et al*.1998). Both marine and freshwater eutrophication can have negative effects on aquatic and terrestrial ecosystems, and may be detrimental to the health of humans. Excessive aquatic weeds, algae and zooplankton may interfere with water utilisation such as consumption, recreation, subsistence and commercial farming, and industry (Carpenter 1998).

Riparian buffer zones have been recognised as the most successful attenuation mechanism for agriculturally derived non-point source nitrate (Hill 1996). Riparian buffer zones are vegetated areas adjacent to streams, lakes and rivers, that are managed to enhance and protect aquatic resources from the adverse impacts of agricultural practices (Castelle *et al.* 1992; Bren 1993). Although much research has focussed on the mechanisms of nitrate attenuation in riparian buffer zones, there still lacks sufficient guidelines towards the sizing and management of the zones specifically for the function of nitrate attenuation.

Reviews by Castelle (1994), Palone and Todd (1997), and Dosskey have suggested a range in buffer widths required for the desired buffer functions (Figure 1). The recommended minimum riparian buffer width for achieving good nitrate attenuation ranges from five metres to ninety metres. This large range in recommendations regarding riparian buffer zone sizing for nitrogen attenuation, and more specifically nitrate attenuation, makes implementing these zones for successful pollutant management a difficult process. For example, riparian buffer zones in North Carolina, USA have proved very efficient in attenuating nitrate, where more than 94% of the nitrate was removed by the buffer zone processes (Peterjohn & Correll 1984). Yet buffer zones in New Zealand were found by Cooper (1990) to be less efficient, where less than 15% of the nitrate was attenuated. The variation in these findings may be attributed to the design and sizing of the riparian buffer zones.

If nitrate attenuation is a management objective, then standardised guidelines for the design and establishment of these riparian zones specifically for this function are necessary. A better understanding of the characteristics in riparian buffer zones responsible for enhancing nitrogen attenuation may assist in narrowing the range of minimum buffer widths recommended, and in achieving site-specific width estimates for attenuating more than 75% of the nitrate entering the environment.

Figure 1

Recommended buffer sizes for specific riparian functions (after Castelle et al. 1994; Palone & Todd 1997; Dosskey et al. 2000)

Objectives and approach

The research is aimed at developing guidelines that will facilitate recommendations regarding the establishment and management of riparian buffer zones specifically for the removal and immobilisation of nitrate, particularly within an agricultural context. The objective is to demonstrate a means of assessing riparian areas and sizing riparian buffer zones specifically for the function of nitrate attenuation.

The methods are inductive, and are based primarily on a literature review, with limited testing of the proposed approach. The available studies and experiments relating to the topic were collated, and entered into a data base system. One hundred and fifty entries to the data base were made using studies from the United Kingdom, New Zealand, Canada, France, Australia, and over 14 different sites in the United States of America. The purpose of this system was to compare available data, and isolate similar characteristics promoting nitrate removal and retention within riparian buffer systems.

Developing the database was problematic, as the variety of definitions for riparian environments meant that the actual riparian environments used in studies varied greatly. The studies were also conducted all over the world, meaning that the different topographies; climates; soils; vegetation; measurement techniques and units often interfered with gaining the necessary information regarding nitrate attenuation from the studies. The objectives of the studies often differed too, where a variety of methods were used. Thus the lack of common criteria used by these studies make comparisons difficult.

The buffer zone characteristics found to be most responsible for promoting nitrate removal or immobilisation were used to develop an example of a means of assessing nitrate attenuation in any given landscape. Such an assessment will allow the user to identify which of these characteristics promoting nitrate attenuation are present or absent within their existing riparian system. Once the current nitrate attenuation for a site is evaluated, it is possible to design a site-specific riparian buffer system of suitable width and composition for the improved attenuation of nitrate. A set of guidelines were developed as based on riparian characteristics promoting nitrate attenuation. These guidelines are proposed as a means of assisting riparian buffer zone assessment and design for nitrate removal or retention.

Understanding nitrate attenuation processes in riparian buffer zones

It is generally recognised that both organic and inorganic nitrogen from agricultural surface and subsurface flows can be trapped by riparian buffer zones (Osborne & Kovacic 1993; Barling & Moore 1984; Hill 1996; Dosskey *et al.* 1999; Karssies & Prosser 1999; Klapproth 1999). Yet there is relative uncertainty regarding the key mechanism responsible for the removal or immobilisation of nitrate in riparian land environments. Evidence (Lowrance *et al*. 1984a, 1984b; Peterjohn & Correll 1984; Cooper 1990; Jordon *et al.* 1993) suggests that nitrate depletion in riparian ecosystems is not only the result of its conversion to other soluble forms of nitrogen, as loss of nitrate recorded in riparian areas is seldom associated with increased amounts of NH^{+}_{4} and organic N in subsurface water. Riparian environments are therefore important sinks for nitrate removal and retention. Denitrification, assimilation and retention by vegetation, nitrification, and mineralisation or transformation to ammonium and organic nitrogen, are all processes noted to retain, remove or immobilise nitrate (Correll 1997).

Generally, it is two key processes which are most notably recognised in the available literature, either individually or together, for immobilising and/or removing nitrogen from surface and subsurface flows:

- The retention or immobilisation of nitrogen by plants and organisms (vegetative uptake) as recognised by Hemond and Benoit (1988); Peterjohn and Correll (1984); Lowrance *et al*. (1984b); Fail *et al.* (1986). Important characteristics of riparian vegetation for the determination of uptake potential include the structure, density and condition of the plants (Karssies & Prosser 1999).
- The removal of nitrogen into the atmosphere through the process of denitrification is discussed in studies by Jacobs and Gilliam (1985); Cooper (1990); Ambus and Lowrance (1991); Haycock and Pinay (1993). Important characteristics of riparian buffer zones improving the potential for denitrification include an availability of nitrate and organic carbon, and anaerobic soil conditions for at least some of the time (Lowrance 1992; Schipper 1994; Correll 1997).

A database of the available literature was established for means of riparian buffer zone comparison. Information from the database was graphed in an attempt to isolate the characteristics most notably responsible for improving nitrate attenuation in riparian buffer zones. Comparisons of studies finding high nitrate attenuation efficiencies (greater than 60% of the nitrate attenuated) suggested that riparian nitrate attenuation world-wide is a result of the combination of three common riparian zone characteristics, namely: the delivery pathway of water and solute nitrate; the vegetation structure; and the soils.

Delivery pathways: studies where there was shallow lateral subsurface (Figure 2) or uniform surface delivery pathways showed the most significant nitrate attenuation efficiencies. Figure 2 shows the findings of many studies, where study sites containing a shallow confined aquifer are distinguished from other riparian geologies. The nitrate retained by the buffer zones was measured as a percentage, and is graphed against the width (in metres) at which the percentage was recorded. The nitrate removal efficiencies of the riparian zones with a shallow confined aquifer are generally very high (greater than a 60% removal efficiency). This might be a result of the shallow lateral flow systems promoted by the presence of the shallow aquifer, where the nitrate is in close contact with the biologically active surface soils and vegetation of the riparian zones. The processes of vegetative uptake and denitrification are promoted in this environment.

Figure 2

The influence of shallow, lateral subsurface flow on the nitrate removal efficiencies of riparian zones. Created using the findings of many study sites around the world

Vegetation structure: The choice of vegetation type for the nitrate removal function of riparian buffer zones has led to much debate. There are many studies (Groffman *et al.* 1991; Haycock & Pinay 1993; Osborne & Kovacic 1993; Schnabel *et al*. 1996; Schnabel *et al*. 1997) throughout the world relating to the topic, and most focus specifically on the nutrient retention or removal abilities of *forested* versus *grassland* buffer zones. Research to date does not allow for a definitive answer as to which vegetation type is more suited for nitrate removal or retention (Figure 3). Figure 3 compares the removal efficiencies of riparian zones of differing vegetation types, but shows no clear indication that any one vegetation type is particularly effective at nitrate attenuation.

Figure 3

Graph indicating the effect of vegetation type on the nitrate retention or removal functions of riparian *zones studied by various authors around the world*

But the studies did suggest that good vegetation composition and structure was important in retaining surface and subsurface water in the riparian environment, and allowing for vegetative uptake to occur. Studies suggest that vegetation provides decaying organic matter to the soil for oxygen depletion to occur (Cooper *et al.* 1995). Organic matter also supplies carbon as an energy source to fuel the denitrification process (Palone & Todd 1997).

Soils: organic soils tend to be more influential in nitrate attenuation than mineral soils. Figure 4 shows the percentage of nitrate retained by the riparian zone per each month of a study by Cooper (1990). The two soils types (organic or mineral) are differentiated by colour, as depicted. It is evident from the graph, that a greater percentage of nitrate was removed from flow systems entering the organic soils, than from the mineral soils in the study. The organic soils promoted nitrate retention.

Figure 4

The effect of soil type (organic or mineral) on the nitrate removal efficiency of a riparian zone in New Zealand, as found by Cooper (1990). The study was conducted over a period of 12 months

Guidelines for assessment and width determination

Riparian rehabilitation or creation can be an extremely daunting task, especially when large reaches of river have been degraded by poor land management or neglect. It is often difficult to determine not only where to place riparian buffer zones, but also how to start rehabilitating; revegetating or improving the chosen sites. A set of guidelines have been developed as based on the findings of the literature review, and are designed as a proposed means to assist farmers and similar landowners in riparian buffer zone creation for the retention or removal of nitrate. The guidelines are set out as three steps (Table 1). The first two steps of the guidelines can be used to set prioritised management zones, and then help assess the current nitrate attenuation efficiency of the site. If a management zone is of high priority, and it’s current nitrate attenuation efficiency is poor, then establishing a riparian buffer zone on that site may be a good conservation practice for nitrate attenuation. However if the current nitrate attenuation of a management zone is found to be good, then establishing a buffer zone on that site is unnecessary. The user will continue onto the third step of the guidelines only if the management zone in question will benefit from a riparian buffer zone. Although there is a large literature base on how to establish riparian buffer zones, there is little consensus on how to size a riparian buffer zone specifically for improved nitrate attenuation. The third step to the guidelines proposed can be used to estimate a more accurate buffer width for a specific management zone.

Table 1

Prioritising and assessing management zones

Step 1. To establish prioritised riparian management zones

With nitrate attenuation as a management objective, the first logical step would be to divide the given agricultural area into smaller, more-manageable units, and to prioritise sections of river for rehabilitation or buffer zone creation. The nitrate loading and delivery pathways of water will give a better indication of management zone priority.

Step 1a) To delineate the catchments

The first part of ***Step 1*** requires that the micro-catchments be defined. With topographical maps and orthophotographs of the agricultural area, the drainage lines and watersheds can be marked using either manual or GIS techniques. As nitrate is a solute, it will reach the river system either in surface or subsurface flow (Prosser *et al.* 1999c). The micro-catchments will give a better indication of the where the water is coming from, as well as the direction of the flow and the way in which it enters the river system. Because water in each micro-catchment has a common watershed and drainage area, the micro-catchments can each become individual management zones.

Step 1b) To identify the nitrate loading within each management zone

Nitrate in agricultural runoff is most often derived from non-point sources. The non-point source nitrate characteristics will give an indication of the potential nitrate loading for each management zone. The nitrate loading usually refers to the mass of nitrate per unit area, which can be measured over a period of time. The solute nitrate will move through the drainage system, and the loading can ultimately be measured at a drainage point in milligrams per litre. Although the actual loadings can be calculated given sufficient information, the approach taken for the purpose of this research is to obtain a relative measure of loading.

For example, the extent of the landuse within each management zone can be used to gain a relative measure of the current loading rates, where source density, intensity and magnitude can be rated (Table 2). Source density might be the number of different source areas in the management zone, source intensity might be the frequency of fertilizer applications, and source magnitude might be the mass of fertilization per unit area. There is a fairly extensive literature base regarding various types of landuses, crops and agricultural practices, and the associated nitrate loading rates (Palone & Todd 1997). The area of each landuse in the management zone can be calculated from the orthophotograph or map, and the nitrate loading rate per unit area can be estimated. By summing and averaging the loading rates per unit area for each landuse, an average nitrate loading rate for the management zone can be estimated. Loading rates vary in response to fertilizer applications. Most agricultural crop products require fertilization, and fertilization schedules can be acquired for the farm or agricultural area. These schedules can help more accurately predict the loading rate in each management zone.

Table 2

The three factors used in this example (Table 2) may give a better indication of the current nitrate loading of a management zone. The greater the source density, intensity and magnitude of the various landuses, the greater the potential nitrate loading rate per unit area. High loading rates within management zones may indicate a greater priority for buffer zone establishment, whereas current loading rates of lower ratings may indicate that buffer zone establishment for those management zones are of less priority.

Step 1c) To identify the delivery pathways within each management zone

The delivery pathway of water is very important when trying to prioritise management zones, as it can greatly influence a riparian buffer zones ability to attenuate nitrate. It has been established through the literature review that when the delivery pathway of water passes through the root zone of the riparian buffer, soluble nitrate is made available for vegetative uptake and denitrification. However when the delivery pathway of water bypasses this zone, nitrate removal is negligible. It is therefore important to determine the local geology of the micro-catchment. If the water follows a deep flowpath, bypassing the root zone of the riparian area, then a proposed riparian buffer zone will be ineffective at nitrate attenuation, and the management zone should no longer be considered for this type of nitrate management. If however, the local geology promotes shallower flowpaths, then the management zone may remain a potential priority for riparian buffer zone establishment.

Step 1d) To order management zones according to priority

The management zones should be ordered according to priority, where highest nitrate loading to a management zone will receive the highest priority (***Step 1b***), provided the delivery pathway of water for that management zone brings nitrate into contact with the riparian area (***Step 1c***). Other factors like the proximity of natural wetland systems, other riparian corridors or important habitats in terms of terrestrial or aquatic conservation should also be noted. Management zones affected by these should be given higher priority. The riparian management zones are established and prioritised. The current nitrate attenuation of the highest priority management zones should at this stage be assessed. The following step in these guidelines is an example of how to achieve this.

Step 2. To estimate the current nitrate attenuation in each management zone

With an understanding of the influential factors in nitrate attenuation in riparian buffer zones, it is possible to estimate the current nitrate attenuation rate of a specific site. The factors known to influence the processes of vegetative uptake and denitrification, can be used to determine how well these mechanisms of nitrate attenuation are functioning. Once the management zones have been prioritised (***Step 1***), the current nitrate attenuation in each zone can be estimated using the following assessment (***Step 2***). The assessment requires that the user rate various influential factors, which are then scored and summed. The eventual score is an estimate of the current nitrate attenuation efficiency of that site, and this estimate will give an indication as to whether a buffer zone will be of benefit to the management aim. There are two parts to the assessment, each part focusses on one of the two key mechanisms of nitrate attenuation in riparian buffer zones. Each of the two parts are reduced to a score out of five. The two parts are summed at the end to give an overall estimate of a site's potential to attenuate nitrate out of ten.

$$\mathbf{CNA = DR + VR} \tag{1}$$

where:

CNA = Current nitrate attenuation

DR = Denitrification rating

VR = Vegetative uptake rating

Step 2a). To estimate the current denitrification rate of a management zone

The process of denitrification requires three things (Chapter 3), namely:

- the availability of nitrate to be utilised by microbial populations in the process of respiration

- anaerobic soils for most of the time, such that nitrate is utilised by the microbial populations as an electron acceptor instead of oxygen for the process of respiration
- the availability of organic carbon for the microbial populations, to be utilised in the process of denitrification.

The nitrate loading of a management zone is assessed in ***Step 1b***, and will contribute to the management zone being prioritised for buffer zone establishment for nitrate attenuation. As such, if the management zone has reached this part of the assessment, then it is assumed that the zone is a priority, and nitrate is therefore available for denitrification to occur. The second two requirements are used to determine a site's potential for denitrification (Table 3). It is assumed that they are of equal importance and are therefore rated equally. To comply with the rating format in ***Step 2b***, the score for each requirement is halved.

$$\mathbf{DR = (SI \times 0.5) + (OMC \times 0.5)} \qquad (2)$$

where:

DR = Denitrification rating

SI = Saturation index

OMR = Organic matter content

Saturation index

The soil oxygen content can be determined on a site by the saturation index of the soil. If the soils are permanently saturated, then the process of decay is hindered and there will be little available organic carbon for the process of denitrification. If the soils are seldom saturated then there will be too much oxygen available for microbial respiration. For this reason soils that are almost always saturated provide the optimum environment for denitrification.

Organic matter content

The availability of carbon is the third requirement for the process of denitrification. Organic carbon is made available through the process of decay, and therefore a high organic matter content will provide the soil with available carbon. The higher the organic matter content, the greater the potential for denitrification, and the better the score.

Table 3

Step 2b). To estimate the current vegetative uptake rate of the management zone

Three factors were noted in the literature review as important in the ability of plants to trap and absorb nitrate as a solute. These factors included:

- the permeability of the soil
- the delivery pathway of water
- the existing vegetation structure

These factors can be rated and scored (Table 4) in the same way as those in ***Step 2a***. The scores are each weighted, and then summed to give an estimated rating of the vegetative uptake taking place in the management zone. It is assumed that each of the three factors are of equal importance and they are therefore weighted accordingly.

$$\mathbf{VR = (SP \times 0.330) + (WDP \times 0.330) + (VS \times 0.330)} \qquad (3)$$

where:

VR = Vegetative uptake rating

SP = Soil permeability (Equation 4)

WDP = Water delivery pathway (Equation 5)

VS = Vegetation structure (Table 4.11)

Table 4

Soil permeability

The ease at which water moves through the soil will influence the water retention time, and the nitrate availability for vegetative uptake. Two characteristics of the management zone have been chosen to help decide how easily water is retained in the soil, namely: the runoff potential of the soil and the slope. It is assumed that the runoff potential and the surface gradient are of equal importance in influencing the ease of water movement through the soil, so the scores are summed and halved to comply with the rating systems of each of the other factors.

$$\mathbf{SP = (RP \times 0.5) + (S \times 0.5)} \qquad (4)$$

where:

SP = Soil permeability

RP = Runoff potential

S = Slope

The runoff potential of the soil will indicate the potential for the soil to allow for infiltration, or its permeability. The inherent capacity of soils devoid of vegetation to allow for infiltration can be estimated according to the hydrologic soil group to which the soil belongs. A hydrologic soil group refers to soils grouped according to their runoff-producing characteristics (Palone & Todd 1997), and will therefore give an indication of infiltration potential. It is the saturated hydraulic conductivity and the internal free water occurrence of the hydrologic soil groups that influences infiltration (Figure 5).

Figure 5

Characteristics of the hydrologic soil groups relevant to this research

The infiltration rate of the soils when thoroughly wet decreases from Group A to Group D. Soils in Group A are mainly deep, well drained and sandy or gravelly. Water moves very easily through these soils, and runoff potential is low. The water infiltrates to the deeper layers more easily as the depth to the water table is usually greater than two metres in soils of Group A (Palone & Todd 1997). Water and solute nitrate is not retained in the biologically active layer of these soils, or the riparian root zone for very long. Soils in Group D tend to have a claypan or clay layer at or near the surface, with permanently high water tables (less than 60cm), or they are very shallow over nearly impervious bedrock (Palone & Todd 1997). Subsurface water is forced to remain as shallow flow, and is retained within the biologically active layer of the soil and the riparian root zone for longer periods of time. But the runoff potential of these soils is high, such that surface flow may not infiltrate the soils at all.

The soils of Group's B and C will allow water to infiltrate the soils (their runoff potentials are average and medium respectively), but the water tables in these soils are considerably shallow (between 0.6 metres and 1.2 metres). The average to medium infiltration rates will promote solute nitrate trapping from surface flows, and water will remain considerably shallow making vegetative uptake more possible. Therefore these soils receive a good score (Table 4), as their inherent permeability is more favourable for vegetative uptake than those of Groups A and D.

The potential for infiltration is further influenced by the gradient. A slope rating is added to the hydrologic soil group rating to include for this influence. The surface flow velocity increases with steeper slopes, and reduces the possibility of infiltration. The retention time of the water in a riparian area is also lessened with an increase in slope. A slope greater than 15% is considered moderately steep with an average water retention time, and therefore of average nitrate attenuation enhancing abilities (Castelle *et al*.1994; Palone & Todd 1998; Klapproth 1999). The ratings and score were set accordingly.

Water delivery pathway

The delivery pathway of water will most definitely influence a riparian buffer zones ability to attenuate nitrate. ***Step 1c*** determined whether water bypasses the riparian area or not. Only catchments where delivery pathways (both surface and subsurface) pass through the riparian zone are considered here. The assessment considers both flow types, which are each given an equal weighting as it is assumed that both are equally influential in nitrate retention by vegetative uptake. The scores for each are summed and halved to comply with the rest of the assessment.

$$\mathbf{WDP = (SSF \times 0.5) + (SF \times 0.5)} \qquad (5)$$

where:

WDP = Water delivery pathway

SSF = Subsurface flow

SF = Surface flow

Subsurface flows (SSF) are often retained in riparian buffer zones because of the reduced surface gradient at the river level. Subsurface flow following shallow lateral delivery pathways will be easily reached by root systems for uptake by plants (Jacobs & Gilliam 1985), and nitrate will be utilised by microbial populations in the biologically active layers of the soil (Haycock & Burt 1993). RBZ's in this environment would be most effective at attenuating nitrate, and micro-catchments with this geology will receive a score of 5 (Table 4). However subsurface flows following deeper delivery pathways may bypass root systems of grass species and the biologically active layers of the soil. RBZ's established in micro-catchments with geologies promoting deeper delivery pathways would only be effective at attenuating nitrates if planted with deep rooting trees. This flow type receives a score of 1.

Surface (SF) run-off may be both channelled or dispersed. Vegetation will be most influential in trapping dispersed surface runoff, and promoting its infiltration, where it will then be made available for plant uptake or denitrification (Karrsies & Prosser 1999). Surface runoff travelling as sheet flow receives a good score (Table 4). Nitrate in channelled surface flow is less easily trapped by riparian vegetation, and receives a lower score.

Vegetation structure:

The structure of the vegetation will influence how easily the delivery flow path of water is reached, and how well soluble nitrate is trapped or utilised by the plants. The literature review suggested that the type of vegetation was not necessarily as influential in nitrate attenuation as vegetation structure. Four factors influence vegetation structure, namely: rooting depth and density, stem density and leaf litter content.

Plants of varied root systems and dense stem densities, that provide good groundcover provide the optimum potential for nitrate attenuation in plant uptake. Plants of varied ages, that frequently provided leaf litter to the soils for improved organic matter contents and available carbon, will promote the process of denitrification. The sum of the four factors will give a rating out of a maximum of 20. This rating needs to be scored as the other factors have out of 5, so as not to affect the weighting (Table 4).

Step 2c). To estimate the current nitrate attenuation

The assessment requires that ***Step 2a***, which is a site estimate for denitrification rates (DR) out of a possible score of five, be added to ***Step 2b***, which is a site estimate for nitrate attenuation by vegetative uptake (VR) out of a possible score of five. The total score out of ten will give an indication of the current nitrate attenuation of that management zone (Table 5).

If a management zone has an average to very poor potential for nitrate attenuation, then it is more important that a riparian buffer zone is designed for that management zone. Management zones receiving higher ratings are already functioning fairly well at nitrate attenuation, and designing and establishing riparian buffer zones for these management zones is of less priority. Therefore if the current nitrate attenuation of a management zone does not score 8 or more (where more than 70% of the nitrate is currently being attenuated), the user should continue with ***Step 3*** of these guidelines.

Determining riparian buffer width

Possibly one of the most debated aspects of riparian rehabilitation and design is the determination of adequate buffer width for the desired riparian function. The size or width of a riparian buffer strip greatly affects the effectiveness and sustainability of the buffer (Palone & Todd 1997). Oversized buffers may deny landowners a portion of land, whereas undersized buffers may be ineffective and reduce the value and sustainability of the aquatic resource (Castelle *et al*. 1994). Both situations may be economically and environmentally costly, urging consensus on how to determine the necessary minimum buffer width for a given riparian habitat.

Many of the international recommendations on buffer width determination are based on characteristics of sediment and attached pollutant travel and deposition in surface flow. There is seldom consideration of width determination as based on the attenuation of pollutants in subsurface flows. Width determination should include a specific site evaluation of riparian characteristics responsible for promoting pollutant attenuation. For example, when determining an adequate buffer width for the attenuation of nitrate, the current site potential for promoting denitrification and vegetative uptake should be considered.

The following guidelines have been developed to help determine a practical buffer width for the removal of nitrate specifically from subsurface flows for any given site, where important site-specific information for each criterion is scored.

STEP 3. TO DETERMINE ADEQUATE BUFFER WIDTH

The choice of vegetation for a riparian buffer zone will directly affect the interception of soluble nitrate in surface flow. The vegetation should therefore be of adequate stem and root structure and density to meet this objective. Thus buffer width determination through these guidelines will not consider the characteristics of soluble nitrate in surface flow. The following step will only rate those characteristics of the riparian zone which are influential in subsurface nitrate attenuation.

Four influential factors in the subsurface nitrate removal ability of a riparian buffer zone are considered:

- organic matter content (as a percentage)
- the hydrologic soil group
- slope or gradient of the surface soils (as a percentage)
- the depth of subsurface flow (in cm)

Each factor can be rated, and issued a score for that rating (***Step 3a-d***). Recent reviews on pollutant attenuation by riparian buffer zones (Castelle *et al.* 1994; Palone & Todd 1997; Dosskey *et al.* 2000) suggest that buffer zones narrower than 5 metres are ineffective at nitrogen attenuation (Figure 1). The widest recommended width according to these reviews for the best possible attenuation of nitrogen does not exceed 80 to 90 metres. Based on these findings, it was decided that a buffer width of 80 metres would be the maximum required buffer width for the function of nitrate removal to be effective in a riparian environment. Similarly, it was decided that a buffer width of less than 5 metres would be ineffective at nitrate removal or unsustainable in the long term, even on a riparian site where conditions for promoting mechanisms of nitrate attenuation are at an optimum. As such, the scoring system ranged from 5 to 80 (Table 6). The scores are directly related to the width of the buffer zones, where higher scores will necessitate wider buffer zones. The rating category for each factor doubles in value, and as such, the scores double too.

It is assumed that each of the four factors are of equal importance to the nitrate removal ability of a riparian buffer zone and are given equal weighting (0.25), and the sum of the four weighted scores is a more accurate prediction of a suitable buffer width for the site:

TBW = (OMR x 0.25) + (HSGR RATING x 0.25) + (SR x 0.25) + (SSFR x 0.25) (6)

where:

TBW = Total buffer width
OMR = Organic matter content rating
HSGR = Hydrologic soil group rating
SR = Slope rating
SSF = Subsurface flow rating

Table 6

Step 3a). Scoring the organic matter content

A soil is considered an organic soil if it contains an organic matter content (OMC) of more than 20% (Palone & Todd 1997). The percentage of organic matter in a soil is rated from very low to very high according to Palone and Todd's (1997) description above. The lower scores are given to the more organic soils, as organic matter is important for the process of denitrification, and their presence improve nitrate attenuation (Table 6).

Step 3b). Scoring the hydrologic soil group rating

The characteristics of the hydrologic soil groups were established in ***Step 2b***. Soils are grouped according to their infiltration potential, drainage, level of the water table, and saturated hydraulic conductivity. Soils allowing for infiltration, but promoting shallow water retention are of optimum value to improving nitrate attenuation. Sites with soils of Group C therefore require a smaller buffer than those of Group A (Table 6).

Step 3c). Scoring the slope rating

Both the surface and the subsurface gradients will influence the route and rate of water movement. As most of the site potential for nitrate removal is dependent on the biologically active zone of the soil (in the top few centimetres), it was decided that the subsurface gradient was not as important. For this reason 'slope rating' is simply the average surface gradient of the given site, and is rated from slight to very steep (Table 6). The water table generally follows the surface gradient of sloping land (Pinay & Burt 2001), which is also influential in nitrate attenuation.

Step 3d). Scoring route of subsurface flow rating

Subsurface water movement influences the nitrate availability for vegetative uptake and denitrification. Subsurface flow (SSF) is rated from *very shallow* to *very deep* (Table 6). The denitrification process is most impressive in the biologically active zone, which is usually in the top few centimetres of the soil. Therefore shallow SSF is given a lower score, as this increases the nitrate removal function of the buffer zone.

Effectiveness of rating system for width estimate

The proposed guidelines and rating system have been based on broad principles and assumptions in the absence of specific understanding. For this reason it was necessary to apply the site characteristics of existing studies to the rating system. In this way it is possible to assess the performance of the system, and account for the criteria chosen for the rating system. Studies that reported nitrate removal efficiencies of 65% to 100% have been used, as the buffer widths of these environments have proven extremely efficient at the task of nitrate attenuation. The site characteristics of each study were rated in the buffer width estimate rating system of ***Step 3***. The rating system estimates a riparian buffer width for a particular site that will be adequate at attenuating more than 65% of the nitrate entering the riparian environment. This width estimate was then compared to the actual buffer widths used in the studies (Table 7, Figure 6).

Table 7

Figure 6

The performance of the rating system when compared to the findings of existing international studies. The Pearson Correlation Coefficient is equal to 0.829, and significant at the 0.01 level

Conclusions

The objective of this research was to develop a proposed means of assessing and sizing riparian buffer zones to achieve a reasonable nitrate attenuation efficiency (>65%). Guidelines were developed as an example of assessment of existing nitrate attenuation potentials of any given site. The findings of such assessments would be useful for riparian design, sizing, establishment and management for improved nitrate attenuation. This research was unable to explore all the design options for improved nitrate attenuation, or recommend specific guidelines regarding buffer establishment. However it did look toward answering one of the most common questions in riparian buffer design: how to determine an adequate width for desired function, by suggesting guidelines for the purpose of nitrate retention.

The wide range in the width recommendations for nitrogen attenuation in the consulted literature suggested that buffer sizing for nitrate attenuation was a daunting task. The proposed guidelines illustrate an approach to determining buffer width, which incorporates current understanding regarding the factors contributing to nitrate removal. The purpose of this research has been to present these guidelines as an approach rather than an explicit system of assessment, as considerable further testing is required. The selection of factors and their weighting may thus vary as more experimental evidence comes to light. Guidelines such as these can be integrated into a more holistic management strategy for water quality protection, where water users such as Catchment Management Agencies may use information like this in the development of a Catchment Management Strategy.

Recommendations

This research is exploratory in nature and consequently there are several areas for further investigation. The recommendations arising from this research are bulleted below.

- The lack of common site information documented by researchers makes any form of riparian studies comparison very difficult. It is recommended that a list of key site criteria be developed, which researchers are required to document in all riparian studies regarding nitrate attenuation.
- A standardised methodology for measuring nitrate attenuation in riparian buffer zones should be created, for means of easier research comparison.
- Further research into the similarities of effective riparian buffer zones will indicate more conclusive characteristics responsible for enhancing the mechanisms of nitrate attenuation. Similar research may be conducted on the functions of sediment and phosphorous trapping by these zones.
- An instruction manual with a set of guidelines specific to the South African context should be developed. The set of guidelines should assist in the sizing, shaping, establishment, management and monitoring of riparian buffer zones for the specific function of nitrate attenuation.
- Similar research into developing guidelines for the management of other water pollutants derived from agricultural landscapes is also achievable. It is recommended that the design of riparian buffer zones for the attenuation of sediment and phosphorous be considered for similar instruction manuals.

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FIGURES AND TABLES

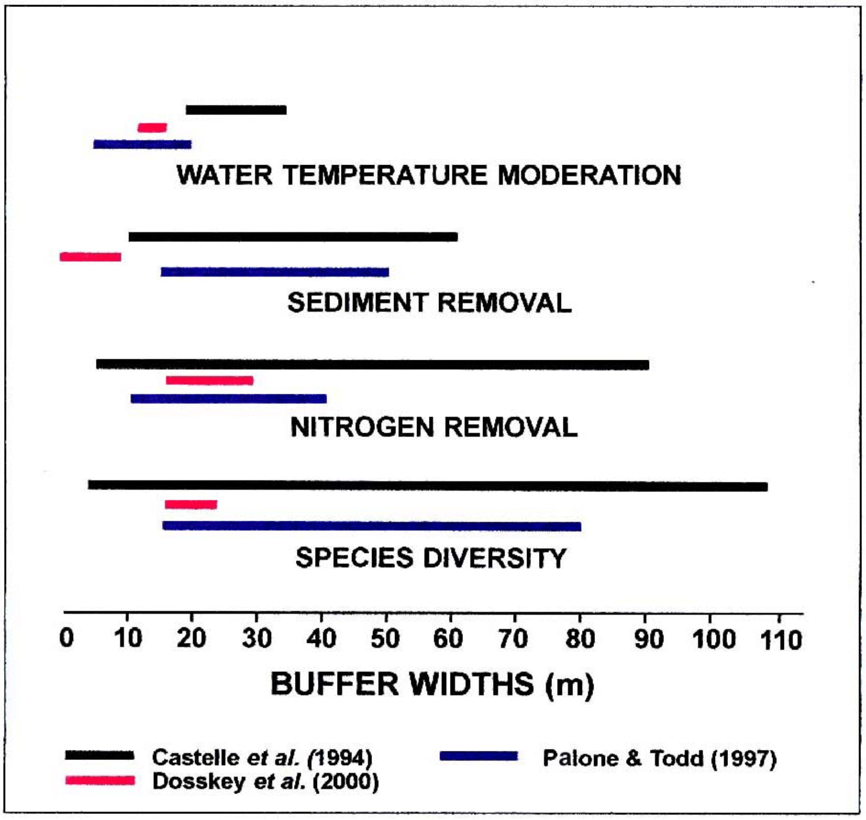

Figure 1

Recommended buffer sizes for specific riparian functions (after Castelle et al. 1994; Palone & Todd 1997; Dosskey et al. 2000)

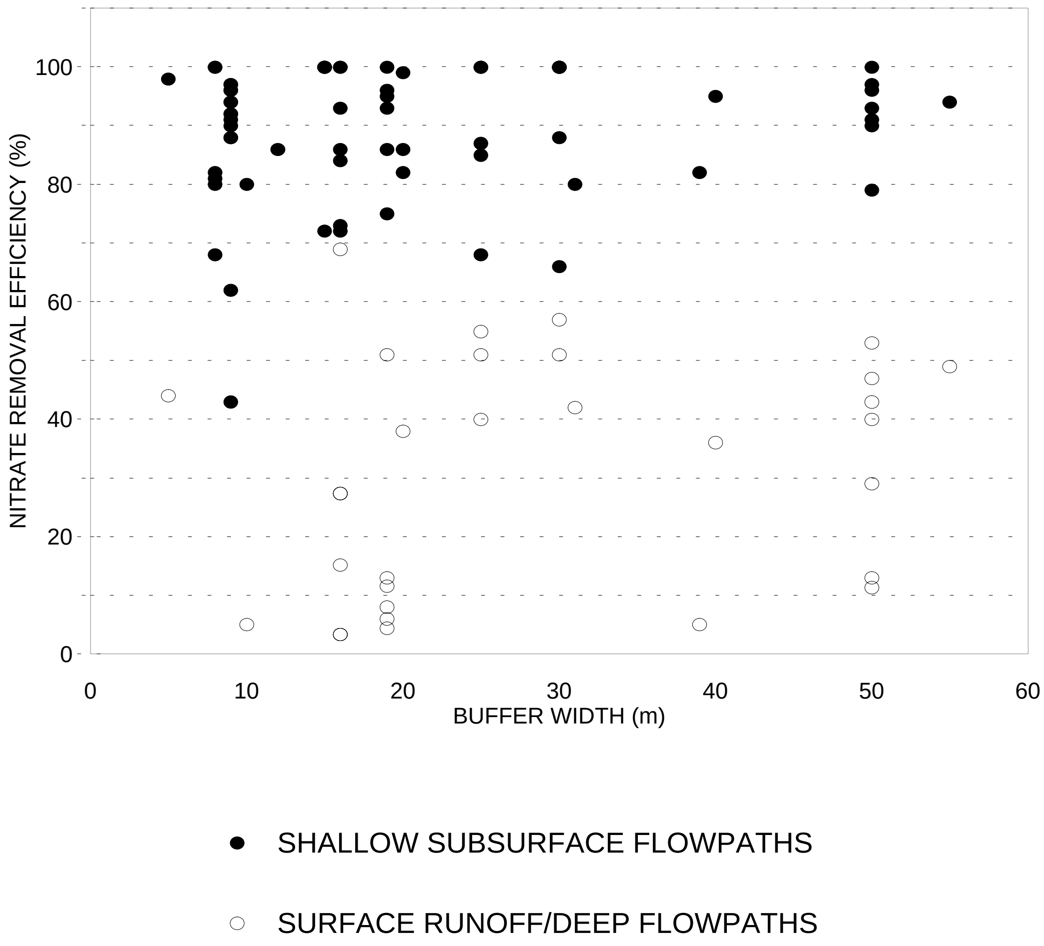

Figure 2

The influence of shallow, lateral subsurface flow on the nitrate removal efficiencies of riparian zones. Created using the findings of many study sites around the world

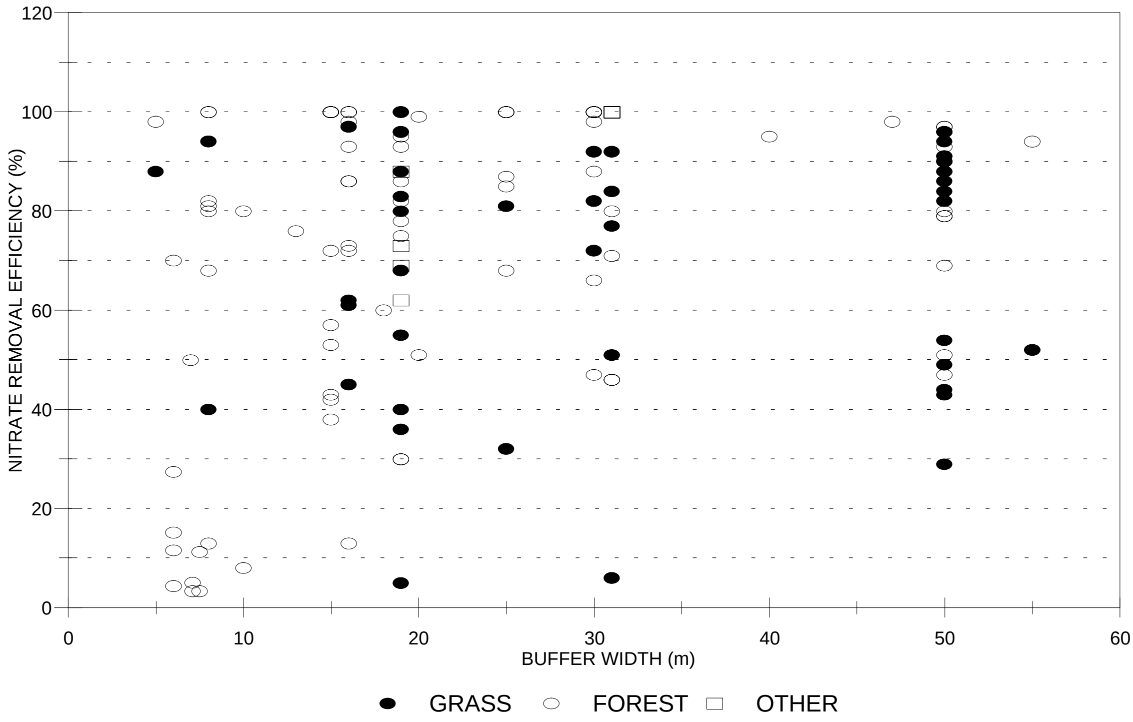

Figure 3

The effect of vegetation type on the nitrate retention or removal functions of riparian zones studied by various authors around the world

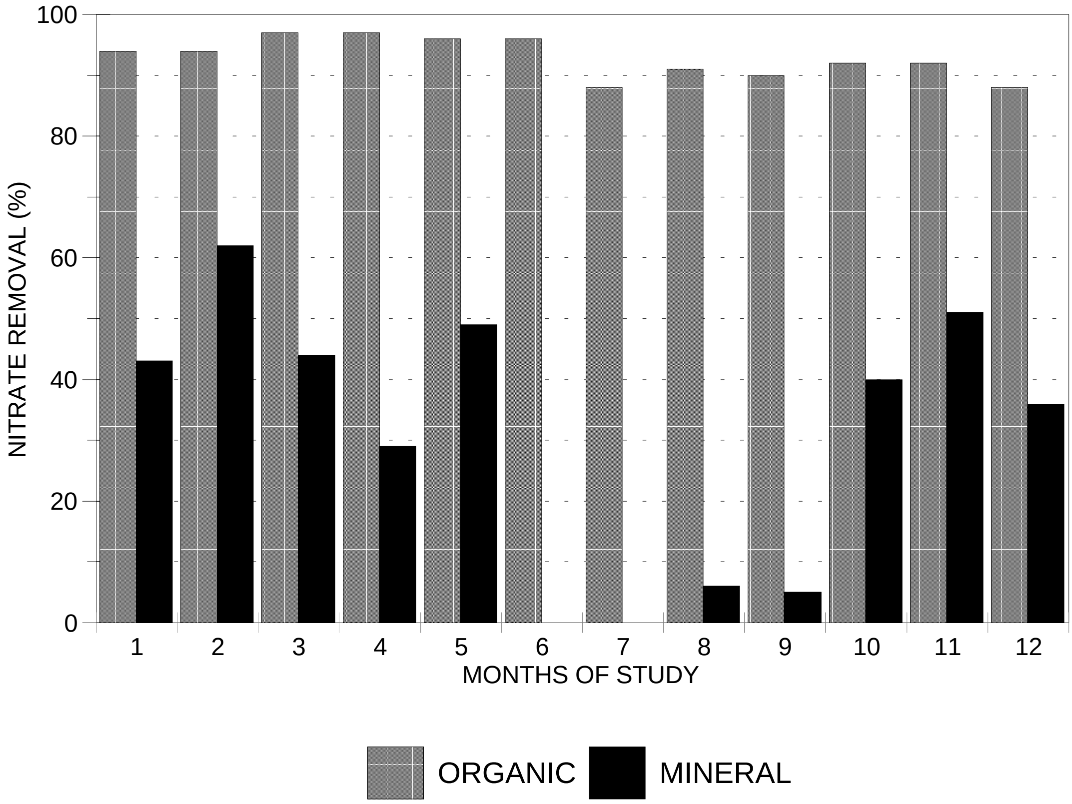

Figure 4

The effect of soil type (organic or mineral) on the nitrate removal efficiency of a riparian zone in New Zealand, as found by Cooper (1990). The study was conducted over a period of 12 months

HYDROLOGIC SOIL GROUP	INTERNAL FREE H_2O OCCURRENCE	SATURATED HYDRAULIC CONDUCTIVITY	INHERENT RUNOFF POTENTIAL
GROUP A	Very deep	Very high	**Low**
GROUP B	Deep	High	**Average**
GROUP C	Shallow	Moderately high	**Medium**
GROUP D	Very shallow	Moderately low	**High**

Figure 5

Hydrologic soil group characteristics

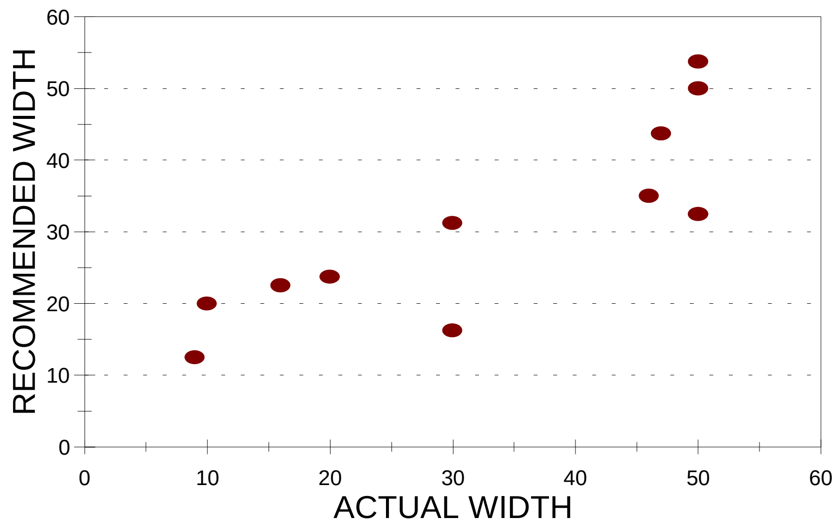

Figure 6

The performance of the rating system when compared to the findings of existing international studies. The Pearson Correlation Coefficient is equal to 0.829, and significant at the 0.01 level

TABLE 1 Guidelines for assessing and sizing riparian buffer zones specifically for nitrate attenuation	
STEP 1: **To establish prioritised management zones**	Step 1a: Delineate the catchments Step 1b: Identify the nitrate loading in each management zone Step 1c: Identify delivery pathways in each management zone Step 1d: Prioritise management zones
STEP 2: **To estimate current nitrate attenuation in each management zone**	Step 2a: Estimate current denitrification rate Step 2b: Estimate current vegetative uptake rate Step 2c: Score current nitrate attenuation
STEP 3: **To determine a buffer width capable of attenuating >75% of the nitrate**	Step 3a: Score organic matter content rating Step 3b: Score the hydrologic soil group rating Step 3c: Score the slope rating Step 3d: Score the subsurface flow rating

TABLE 2

Example of how to establish the current nitrate loading rate of the management zone

	High	Medium	Low
Density	3	2	1
Intensity	3	2	1
Magnitude	3	2	1
Score = 3 Density; Intensity; Magnitude			
Score	7-9	4-6	1-3
Current nitrate loading	**HIGH**	**MEDIUM**	**LOW**

TABLE 3

Estimating the current denitrification rate of a management zone

DR = (SI x 0.5) + (OMC x 0.5)

Determining the saturation index (SI) of the soils				
Almost always	Usually	Seldom	Always	Never
5	**4**	**3**	**2**	**1**
Determining the organic matter content (OMC) of the soils				
Very high	High	Medium	Low	Very low
>30%	15 -30%	7-14%	3-6%	<3%

TABLE 3 Estimating the current denitrification rate of a management zone DR = (SI x 0.5) + (OMC x 0.5)				
Determining the saturation index (SI) of the soils				
5	**4**	**3**	**2**	**1**

TABLE 4 Estimating the current vegetative uptake rate of the management zone VR = (SP x 0.330) + (WDP x 0.330) + (VS x 0.330)					
Determining soil permeability: SP = (RP x 0.5) + (S x 0.5)					
Runoff potential					
Group C	Group B	Group D	Group A		
5	**4**	**3**	**2**		
Slope					
Slight	Gentle	Moderate	Steep	Very Steep	
0-7%	8-15%	16-25%	26-35%	>35%	
5	**4**	**3**	**2**	**1**	
Determining water delivery pathway: WDP = (SSF x 0.5) + (SF x 0.5)					
Subsurface flow types					
Very shallow	Shallow	Medium	Deep	Very deep	
<10cm	11-20cm	21-40cm	41-80cm	>80cm	
5	**4**	**3**	**2**	**1**	
Surface flow types					
Sheetflow	Dispersed	Rilling	Gullying	Canals	
5	**4**	**3**	**1**	**0**	
Determining vegetation structure:					
	Very high	High	Medium	Low	Very low
Rooting depth	5	4	3	2	1
Rooting density	5	4	3	2	1
Stem density	5	4	3	2	1
Leaf litter	5	4	3	2	1
Vegetation structure score = 3Rooting depth; Rooting density; Stem density; Leaf litter					
17- 20	13-16	9-12	5-8	4	
5	**4**	**3**	**2**	**1**	

TABLE 5 Estimating the current nitrate attenuation of the management zone CNA = DR + VR					
DR + VR	8-10	6-7	4-5	3	2
Potential	Very good	Good	Average	Poor	Very poor
Efficiency	**>70%**	**56-70%**	**46-55%**	**36-45%**	**<35%**

TABLE 6 Achieving a site-specific riparian buffer width estimate TBW = (OMR x 0.25) + (HSGR x 0.25) + (SR x 0.25) + (SSFR x 0.25)				
Organic matter content rating				
Very high	High	Medium	Low	Very low
>40%	21-40%	11-20%	5-10%	<5%
5	**10**	**20**	**40**	**80**
Hydrologic soil group rating				
Group C	Group B	Group D	Group A	
10	**20**	**40**	**80**	
Slope rating				
Slight	Gentle	Moderate	Steep	Very steep
0-7%	8-15%	16-25%	26-35%	>35%
5	**10**	**20**	**40**	**80**
Subsurface flow rating				
Very shallow	Shallow	Medium	Deep	Very deep
<10cm	11-20cm	21-40cm	41-80cm	>80cm
5	**10**	**20**	**40**	**80**

TABLE 7

Performance of the rating system for width estimate when using the site characteristics of existing riparian studies

Author	Actual riparian width	Recommended riparian width
Brusch & Nillson (1993)	20	**23.75**
Cooper *et al*. (1986)	16	**22.5**
Corley *et al.* (1999**)**	10	**20**
Dillaha *et al.* (1989)	9	**12.5**
Gambrell (1975)	46	**35**
Jacobs & Gilliam (1985a)	50	**32.5**
Jacobs & Gilliam (1985b)	47	**43.75**
Jordon *et al.* (1993)	30	**16.25**
Lowrance *et al*. (2000)	50	**50**
Peterjohn & Correll (1983)	50	**53.75**
Sloan *et al*. (1999)	30	**31.25**

MINIMISING SEDIMENT DELIVERY TO RIVERS: A spatial modelling approach developed for commercial forestry

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ABSTRACT

Commercial forestry is recognized for both its economic contribution as well as its environmental impact. Of particular concern, is the soil erosion and sedimentation of watercourses associated with forestry plantations. Environmental laws regulate many of the activities of the forestry sector. It is critical that the forestry sector ensures that its operations are compliant with the legal requirements that govern its use of natural resources. In pursuing legal compliance it is necessary to ensure that erosion control strategies are developed so as to ensure the positive effects of any interventions are optimised. The identification of areas that are particularly at risk to erosion or contribute to sediment delivery is an essential component in prioritising areas for management interventions.

Establishing the erosion potential for commercial forestry areas is readily accomplished through the application of existing models. Process based erosion models generally have greater data requirements than the empirically derived USLE-based models. Given the paucity of data available, the latter approach was adopted. Two methods of topographic sub-factor derivation were investigated, those associated with the RUSLE (Renard, Foster, Weesies & McCool 1991) and the Unit Stream Power method presented by Moore and Burch (1986). Since no existing methods identifying delivery risk areas existed, a method was developed based on principles and factors identified in the literature. Additionally, methods for identifying topographic assets, in terms of sediment attenuation, were developed. From these models three indices were derived; sediment supply, delivery risk and sediment attenuation.

Thereafter, the mean Sediment Supply Index was divided by stream length for small catchments defined within the landscape to derive an index of sediment loading to streams. This index is used to identify priorities for management intervention across the landscape. The mean slope and sediment supply is used to develop buffer width recommendations for the streams draining the catchments, using a method developed by Karssies and Prosser (2001). Using the three indices in conjunction it is possible to make on-site and off-site erosion control recommendations as well as identify and exploit any natural features that can be utilized in erosion control.

1 Introduction

Commercial forestry, and its associated industries, are significant contributors to the economy of South Africa, accounting for 4.7% of total export earnings (Lefakane & Pata 1998). In 2001 this amounted to 180 million dollars (US Department of State 2001). The potential of social forestry to contribute to the upliftment of impoverished rural communities has been recognized as an important factor in rural development. The government has an expressed intention to develop its role as a supporter of forestry, especially through social forestry and the small farmer sector (Department of Water Affairs and Forestry 1995).

However, the economic contribution of forestry does have associated environmental costs; water quantity and quality impacts are particularly contentious. The Guidelines for Environmental Conservation in Commercial Forestry in South Africa issued by the Forestry Industry Environmental Committee (1995) acknowledge that soil loss is one of the undesirable impacts of forestry, and the Forest Policy Discussion Document (DWAF 1995) explicitly requires that sustainable forest management include protection of water resources and soils. The African National Congress Agricultural Policy Document (1994) notes that commercial forestry has been implicated in increased soil erosion. It is evident that an awareness of the associated economic benefits and the environmental costs is influencing national policy regarding commercial forestry.

While models for soil erosion have been developed and successfully applied, typically the basis for these models is in the traditional agricultural environment (O'Shaugnessy, Fogarty & Croke 1998). These authors suggest that there are specific conditions relating to commercial forestry that need to be addressed in an evaluation of the impacts relating to soil erosion. An understanding of erosion processes as they relate to commercial forestry is required, so that the potential benefits of forestry can be optimised without compromising the sustainability of the industry by depleting the resources on which it depends. Commercial forestry, in South Africa, is often situated on steeper slopes in the upper areas of catchments adjacent to first order streams. Areas of forestry are exposed to disturbance at a lower frequency, although the disturbance is more severe than traditional agriculture. Of particular significance in South Africa, is that commercial plantations are largely confined to the source areas of many of the rivers that supply the country with water. Both the forestry industry and national interests are acknowledged in the need to manage soil erosion in forestry areas, given the sensitive nature of these areas and the disturbances to which they are exposed.

The extensive networks of roads, often unsealed, associated with commercial forestry areas are a significant sediment source in these areas. For example, Sadek, Grayson and Gippel (1998) report that catchments with unsealed roads produced 10 to 100 times more sediment load per unit area compared with undisturbed catchments. Peak hourly average turbidity during storm events was four to six times that in undisturbed catchments. The temporary lack of vegetation cover during plantation regeneration also contributes to increased sediment loads, although the effect is eliminated once total groundcover is restored to between 40 and 50% of the pre-disturbance levels (Croke & Mockler 1998). In northwestern California, McCashion and Rice (1983) found that roads were responsible for 61% of the soil volume displaced by erosion in logging areas and that the average erosion rate on roads was 17 times the average rate for logging areas. The incidence of mass soil movements has been shown to increase in clear-cut areas throughout the world (Gray 1970).

The environmental performance of the South African forestry industry is governed by the Forestry Stewardship Council (FSC) and IS0 14001 accredited management systems. These international systems require regular auditing of the environmental performance of forestry companies. The requirements of these management systems are implemented through internal Best Management Practices (BMPs). Fulfilment of the requirements of these environmental management systems maintains the South African forestry industry's access to international markets.

The role of buffers, be they simple vegetated filter strips, forested riparian zones or wetland systems, as effective sediment traps has been conclusively established (Castelle, Johnson & Conolly 1994). Simplistically, buffer zones are defined as "a transition zone between areas managed for different objectives" (World Resources Institute 2001). Not only are buffers efficient in improving both water quality and quantity of instream environments, there are additional benefits arising from the responsible management of riparian areas, such as increasing biodiversity, flood attenuation, reducing bank erosion and habitat provision. In plantation forestry there is the additional benefit of these areas acting as firebreaks.

Given the acknowledged impact of plantations, the legal responsibilities of landusers, the international requirements to maintain access to markets and the need to ensure sustainability, the impact of erosion associated with commercial forestry needs to be effectively managed. There is a need for a method that integrates effective management strategies with rational, scientifically based prioritisation procedures to maximize the benefit from management interventions. This method should utilise existing data and available technology, and be easy to implement.

2. MANAGING SEDIMENT DELIVERY TO STREAMS

Managing sediment delivery to streams requires that the problem be addressed in three phases, at the sediment source, during sediment transport and at sediment delivery to streams. Addressing the first phase requires a method for identifying priority areas for erosion control based on the erodibility of the area. To achieve this a Sediment Supply Index is developed indicating erosion potential across the landscape. The transportation phase will be addressed by assessing the localized efficiency of sediment transport across the landscape and identifying specific natural landscape features that have the greatest potential for sediment attenuation. Two indices, the Delivery Risk Index and the Sediment Attenuation Index, are used in addressing the transportation phase. The final phase, sediment delivery to streams, will be addressed by a method for developing buffer width recommendations.

2.1 Identifying sediment sources

The first priority in reducing sediment delivery to streams is to control the erosion at source, preventing the mobilisation of sediment and thus eliminating the possibility of delivery to watercourses. Due to landuse activities, it is not always possible to achieve the above objective. Consequently, it is necessary to identify areas within the landscape that are particularly at risk of eroding and managing them appropriately, so as to minimise the amount of sediment that is mobilised.

The application the Universal Soil Loss Equation (USLE), and its derivatives, the Revised Universal Soil Loss Equation (RUSLE) and the Modified Universal Soil Loss Equation (MUSLE) are commonly used methods for predicting soil erosion[1].

While more complex models that attempt to model the physical processes involved in soil erosion have been developed, they are usually implemented to improve the understanding of erosion processes, or to trace the path of pollutants across the landscape. These include ANSWERS (Beasley, Huggins & Monke 1980), CREAMS (Knisel 1980; Foster, Lane, Nowlin, Laflen & Young 1981), KINEROS (Woolhiser, Smith & Goodrich 1990) AGNPS (Young, Onstad, Bosch & Anderson 1987) and WEPP (Lane & Nearing 1989). The data requirements of these models are more extensive than those of the empirical models. The USLE-based models are used due to data paucity and the fact that they satisfy the requirements for the purposes of this exercise, principally to determine a relative assessment of erosion potential across the landscape.

The USLE equation is given as:

$$A = R \cdot K \cdot LS \cdot C \cdot P \qquad (1)$$

Where

[1] Unless referring to specific revisions of the basic USLE, the modelling procedures undertaken for this dissertation will use the term USLE to describe all models based on the A=RKLSCP formula.

A	=	the computed long term average soil loss per unit area ($t.ha^{-1}.annum^{-1}$)
R	=	an index of rainfall erosivity ($MJ.mm.ha^{-1}.h^{-1}.annum^{-1}$)
K	=	soil erodibility factor ($t.h.MJ^{-1}.mm^{-1}$)
LS	=	combined flow length and gradient factor (dimensionless)
C	=	cover and management factor (dimensionless)
P	=	support practice factor (dimensionless)

Since its publication, the USLE has undergone regular revisions, notably the sub-factor method for estimating cover management factor introduced in 1970, and the inclusion of data from rainfall simulations in 1978. The most major revision of the USLE started in 1985 and was completed in 1991. It resulted in what is known as the Revised Universal Soil Loss Equation (RUSLE). RUSLE retains the basic form of the USLE equation but the derivation of the factors was significantly modified, to include aspects of the process methods (ratio of rill and interrill erosion) developed as part of the Water Erosion Prediction Project (Lane & Nearing 1989). Importantly, the model was computerised and extensive databases developed to accompany the model, which improve its utility in non-prototype conditions (Renard, Lane, Foster & Laflen 1996).

The third adaptation of the USLE presents a modification for event-based estimation of sediment yield, rather than long-term yield predictions. The MUSLE (Williams & Berndt 1977; Williams 1982) replaces the rainfall erosivity factor with a runoff term derived from the event-based runoff volumes and peak-flow rates. It is important to note that neither the original USLE, nor any of the subsequent revisions, is suitable for application in areas that are not sediment supply areas. Figure 1 presents the process flow for deriving a Sediment Supply Index (SSI).

The Sediment Supply Index (SSI) is derived from the application of the USLE-based erosion prediction models (Equation 1), excluding the landcover and support practice factors. The reasons for excluding these factors is that commercial forestry activities regularly create areas within the landscape that are completely denuded of vegetation. Additionally, the need to avoid any implicit criticism of existing landuse practices, identified by Mander, Quinn and Mander (1993), is relevant, and may improve the acceptability of the proposed procedures to the forestry industry.

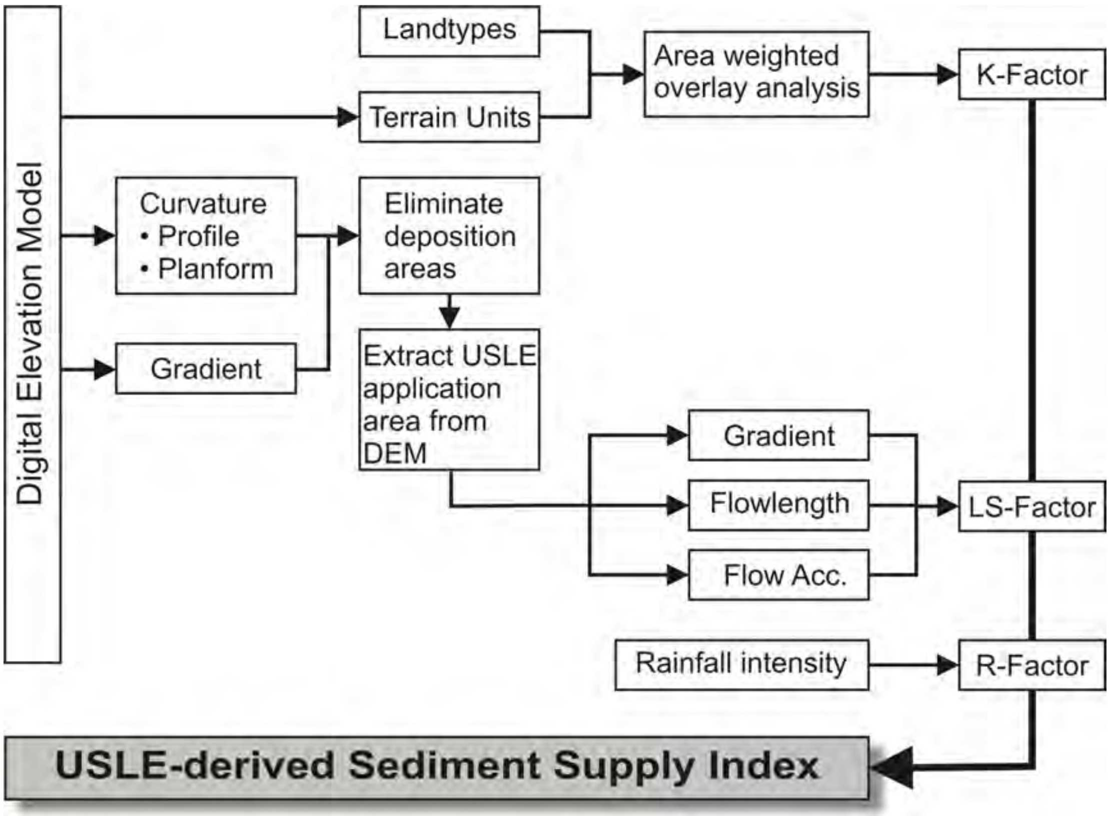

Figure 1: Process for derivation of the Sediment Supply Index

The remaining factors are the rainfall erosivity, the soil erodibility and the topographic (slope-length) factor. These factors required can be readily determined for a particular site. The rainfall erosivity index can been determined in southern Africa by information presented by Smithen and Schulze (1982). Smithers *et al.* (1995) present various methods for establishing the soil erodibility (K) factor. It can be estimated from the soil form and series of the Binomial Soil Classification (McVicar *et al*. 1977), or the form, family and textural class of the Taxonomic Soil Classification (Soil Classification Working Group 1991). It is possible to derive a value for this factor from the soil erodibility class, which was established for southern Africa by the erstwhile Department of Agricultural Technical Services in 1976. Where detailed soils information is available, the nomograph developed by Wischmeier, Johnson and Cross (1971) can be used. This method requires detailed soil particle distribution and percentage organic matter information.

Unlike the factors already discussed, the LS factor has been the subject of much debate regarding the USLE (Moore & Burch 1986; Moore & Wilson 1992; Foster 1994; Moore & Wilson 1994). The reason for the debate is the perceived degree of subjectivity required to determine the flow length (L) sub-factor of the slope length (LS) factor.

The flow length factor is defined as the distance from a point of origin of overland flow to the point where either the slope gradient decreases sufficiently for deposition to take place, or the runoff enters a well-defined natural or artificial watercourse (Wischmeier & Smith 1978). Assessing where channels form, or deposition begins to occur is difficult. It is scale dependent and particularly difficult to accomplish at a catchment scale.

Moore and Burch (1986) interpret the LS factor as a measure of the sediment transport capacity of overland flow. According to Moore and Burch (1986) the empirically derived LS factor for USLE is responsible for inconsistencies and underestimations of erosion that have appeared due to its failure to account for all sediment transport mechanisms. In particular, the inability of the USLE to distinguish between or consider the implication of rill and sheet erosion is seen as problematic. In response to this problem, Moore and Burch (1986) propose a method for deriving the LS factor based on unit stream power theory.

Although the Sediment Supply Index is not a quantitative assessment of erosion, it does use predicted values for developing relative risk assessments that inform the prioritisation process. The identification of areas where it is inappropriate to apply the USLE as discussed above, will improve the identification of priority areas for intervention. This is achieved by eliminating areas where the gradient and terrain morphology are likely to reduce sediment mobility.

It is possible to define a gradient threshold, below which deposition is assumed to occur. Smithers and Schulze (1995) set the gradient threshold for deposition occurrence at 5%. Areas below this threshold are excluded from the area of USLE application, because they are assumed not to be sediment supply areas.

GIS technologies permit the modelling of the terrain morphology from digital elevation models. In the ESRI suite of GIS applications, this modelling function is known as curvature. The curvature function (ESRI 1996) allows for the derivation of information about the topography of the landscape. An index is assigned on a cell-by-cell basis indicating the convexity or concavity at that cell, relative to its eight nearest neighbours. In addition, the function produces two other curvature output datasets.

The profile curvature is the curvature of the terrain in the direction of the slope. It is therefore an indicator of acceleration and deceleration of flow. The planform curvature is the curvature perpendicular to the direction of flow. It indicates the convergence and divergence of flow across the landscape. In all derived datasets, a negative value represents concavity and a positive value represents convexity. The magnitude of the index ranges according to the ruggedness of the terrain.

By developing a matrix of the landform curvature components that occur in a landscape based on the data derived from curvature analysis, it may be possible to identify areas likely to exhibit low sediment mobility. It is assumed that convergent and accelerating slopes increase the mobility of sediment in the landscape. Conversely, divergent and decelerating slopes reduce sediment mobility. There are four possible combinations of the results of the two curvature datasets. In assigning sediment mobility potential to these combinations, a conservative approach was adopted. If either of the factors were regarded as increasing sediment mobility, the combination was assumed to indicate high sediment mobility potential. This means that only the combination of decelerating and divergent slopes is assumed to be indicative of low sediment mobility potential. The proposed matrix is presented in Table 1.

Table 1: Proposed sediment mobility matrix based on the results of the curvature model

		Profile curvature	
		+ve accelerating	**-ve decelerating**
Planform curvature	**+ve divergent**	High mobility potential	Low mobility potential
	-ve convergent	High mobility potential	High mobility potential

By combining the results of the gradient threshold limitation with the results of the curvature analysis it is possible to identify areas of low sediment mobility, which can be excluded from the study area during USLE modelling.

2.2 Delivery risk and sediment attenuation

The Delivery Risk Index is an assessment of the efficiency of sediment transport across the landscape. In order to intercept sediment during the transportation phase, the factors that influence the preferred path for sediment transport need to be assessed. This requires consideration of a number of factors. Firstly, the delivery feature (e.g. the road, waterway or general overland flow), secondly the erodibility of the delivery feature itself, thirdly the degree of connectivity between the stream and the delivery feature, and finally the opportunities for sediment attenuation along the preferred delivery paths.

Road-stream connectivity effectively extends the drainage network within a catchment by establishing new paths for surface flow to enter existing watercourses. Road-stream connectivity influences the efficiency of sediment delivery to streams considerably. Additional impacts relate to alterations in peak flows and the increased likelihood of road-associated sediment entering watercourses.

Besides direct connectivity, i.e. stream crossings, linkages often arise when culverts, or other drainage structures, become linked to watercourses by gully formation at their outlets (Furniss, Flanagan & McFadin 1999; Mockler & Lane 1999; LaMarche & Lettenmaier 2001). Not only do the gullies increase the efficiency of sediment delivery to streams, they are also sources of sediment, and there is an increase in the likelihood of mass failure in the vicinity of gullies. The probability of gully formation is largely determined by the degree to which the flow of culvert output is concentrated by the topography, the convexity or concavity of the landscape. Delivery of sediment into vegetated buffer strips in the form of concentrated flow (as is associated with gullies) considerably reduces their efficiency as sediment traps.

Additionally, the position of the road in the landscape is a contributing factor, with cut-and-fill roads more likely to contribute to sediment production than ridge–top roads (Croke *et al*. 1999). This is partly due to the increase in surface flow as sub-surface flow is transformed into surface flow at the cut-slope of the road, and increased likelihood of mass-failure in both the cut-slope and the fill-slope. Studies have established empirical relationships between the onset of gullies and terrain (Mockler & Croke 1999; Luce & Wemple 2001), but these are site-specific and cannot be generalized across landscapes. These studies rely on intensive data regarding the road drainage structures within the study area, and the observation of sediment delivery over a period of time. Unfortunately, this level of data is generally not available.

Based on the above discussion, and evidence collected in the literature review, five factors that influence the efficiency of sediment delivery to streams have been identified. All the factors are related to the degree of connectivity between the road network and the stream network. The five factors are:

- Actual stream crossings; points where streams and roads intersect
- The level of adjacency between streams and roads; areas where roads and streams run parallel, or in close proximity to one another
- The topographic connectivity between streams and roads; areas where topographic convergence creates links between roads and streams
- The erosion potential of the road surface itself
- The state of the road surface; which combines consideration of the type of surface and the condition of the surface

Figure 2 presents the proposed procedure for developing a Delivery Risk Index based on modelling the factors identified above, and the specific sub-factors that represent them. It presents the primary datasets required for developing the proposed index. The procedures for combining the data to develop the five components of the index, identified above, are also presented. Methods for developing these sub-factors spatially have been investigated.

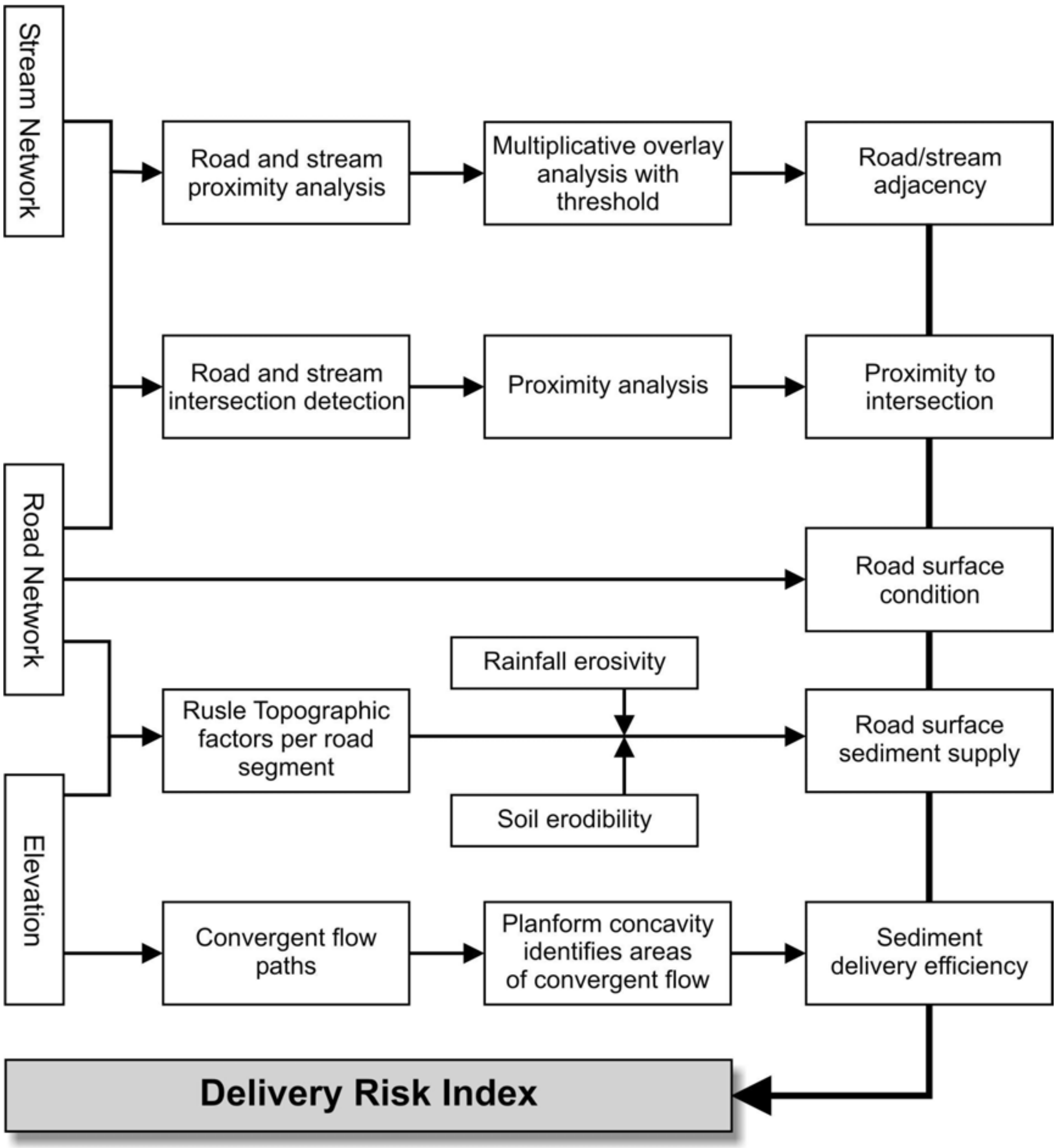

Figure 2: Process for the derivation of the Delivery Risk Index

Topographic sediment traps are areas within the landscape where the terrain morphology, gradient and surface flow patterns can be utilized to perform the service of trapping sediment. These areas may coincide with, but are distinct from riparian zones in that they are not spatially associated with the stream network. They are identified by combining the modelled characteristics of the terrain that would result in areas of low sediment mobility, these being terrain concavity and gradient. Figure 3 presents the proposed method for identifying topographic sediment attenuation features. The areas suitable for sediment attenuation are extracted from the digital elevation model using the curvature and gradient criteria. Suitable areas are assigned a value of 10 for all sub-factors, while unsuitable areas are assigned a value of 1.

The negative areas of the three datasets derived using the curvature function, represent concavity in the landscape while the positive areas represent areas of convexity. The range of values is determined by the ruggedness of the terrain. Areas where sediment attenuation is likely to occur, based on terrain morphology can be identified using the datasets produced which contain profile, planform and localized indices of convexity and concavity.

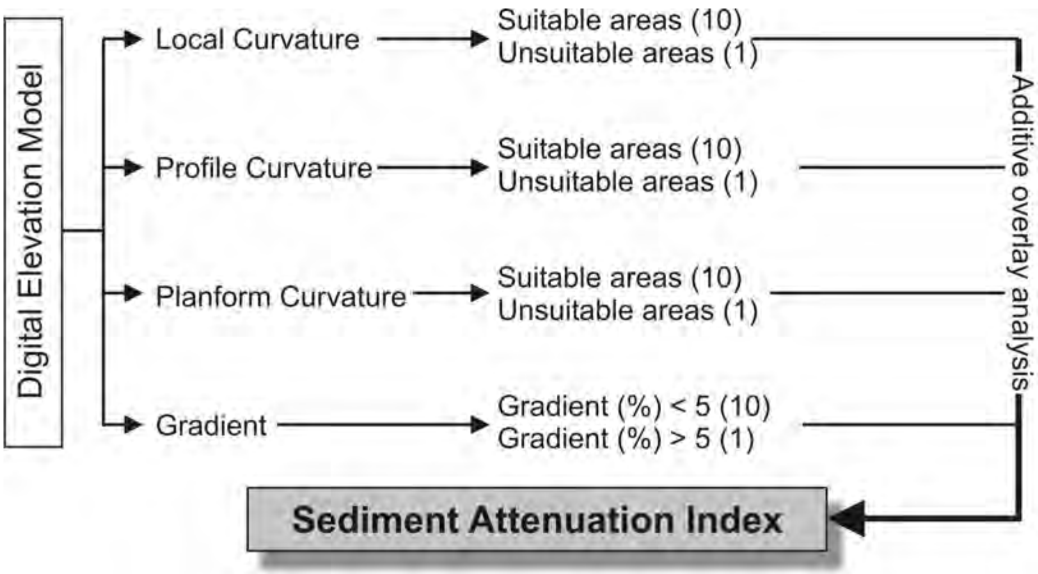

Figure 3: Process for identifying the probability of sediment attenuation features occurring in the landscape showing the sub-factors and their scores

2.3 Minimizing sediment delivery

The final opportunity for reducing sediment delivery to streams is through the use of riparian buffer zones. The efficiency of these areas in reducing sediment delivery, across a wide range of conditions is well established. The tables below presents a summary of experimental evidence relating to the efficiency of buffers as sediment traps.

Table 1: Experimental evidence relating to buffer sediment trapping efficiency

Author	Trapping efficiency	Buffer type and special consideration
Neibling & Alberts (1979)	90%	• Grassed buffers
Young *et al.* (1980)	66 – 82%	• Grassed buffers

Author	Trapping efficiency	Buffer type and special consideration
Magette *et al.* (1989)	52 – 75%	• Grassed buffers
Dillaha *et al.* (1989)	75 – 87%	• Grassed buffers
Cooper *et al.* (1987)	84 – 90%	• Natural forest buffer
Smith (1989)	87%	• Natural forest buffer
Cheschier *et al.* (1991)	90%	• Riparian forest
Ghaffarzadeh *et al.* (1992)	85%	• Vegetative filter strip • Slope effect (7% and 12%) insignificant in buffers wider than 9.1m
Castelle *et al.* (1994)	90 – 95%	• Natural forest buffer • Efficiency has non-linear relationship with buffer width
Gilliam (1994)	85 – 90%	• Natural forest buffer
Lowrance *et al.* (1995)	80 – 90%	• Natural forest buffer
Hairsine (1998)	90%	• Natural forest buffer • 6m wide buffer under variety of flow rates
Croke, Lane, Lacy & Fogarty (1999)	77 – 99%	• Natural forest buffer • Antecedent moisture conditions do not impact efficiency • Surface roughness is critical

In addition to measuring the efficiency of buffers, researchers have investigated a number of factors that influence their efficiency. The key findings are presented in Table 2 below.

Table 2: General findings regarding buffers and sediment control

	Key findings	Authors
Deposition	• Most of the eroded sediment was deposited in the general harvesting area or stream buffer strips • In steep slopes with high sediment yield sediment was deposited up to 19m into the buffer • Fine sediment generated off roads is not trapped by buffers (95% transmission) and should be controlled at source	Wallbrink *et al.* (1998) Dignan (1999) Loch *et al.* (1999)
Condition	• Runoff coefficients were between 5% and 25% on undisturbed buffers and as high as 97% on disturbed buffers • Up to 46% increase in sediment observed in disturbed buffers • Surface roughness is more important than antecedent moisture condition in determining buffer efficiency	Croke *et al.* (1999)
Location	• All drainage lines and watercourses should have buffers between them and any sediment source	Hairsine (1998)

	• The effect of topographic convergence needs to be considered • Proximity to permanent sediment sources needs to be considered	

The length of a watercourse draining a landscape unit, be it a forestry compartment or a small watershed, is an important factor in assessing the sediment risk associated with that watercourse. An area of moderate, or even low, erosion potential (SSI value) drained by particularly short watercourse, may well be at greater risk than a long watercourse draining an area of high erosion potential, because the sediment load to the watercourse is determined by the length over which the mobilised sediment is distributed. This hydrologically related measure can be used to develop a buffer width recommendation that is appropriate to the stream length, based on the localised sediment delivery risk.

Buffer width recommendations need to consider both the amount sediment that is likely to be delivered as well as the localized topography within which the delivery occurs. Karssies and Prosser (2001) present a method for determining buffer width requirements, based on the mechanisms of sediment trapping within buffers. Although not developed specifically for forestry conditions it is the only known method for deriving buffer widths, based on topography and sediment supply that can be readily applied in a GIS environment.

It must be noted that the Karssies and Prosser (2001) widths are based solely on the requirement of sediment attenuation. The results are useful in cases where the existing field buffer is either wider or narrower than the derived buffer width recommendation. In areas where the existing field buffer is narrower than the recommended width, it will be necessary to widen it to at least the minimum recommended width and ensure that the condition of the vegetation is maintained for optimal sediment trapping. Where the existing buffer exceeds the minimum recommended width, it is a matter of ensuring a strip of vegetation that equals or exceeds the recommended width, is maintained for optimal sediment trapping within the existing buffer. In this manner, site-specific buffer width recommendations can be made.

Results suggest that, on average, industry buffer standards are adequate for sediment control. The critical factor is thus the condition of the vegetation within the buffer area. It is important to note that the results suggest that the steep headwater streams are often inadequately protected, while the lower order watercourses are over-protected. This corresponds to Bren's (1999) observation that identified upslope convergent areas as areas that are usually under-protected. This result is controversial as it is a direct contradiction of the Landuse and Wetland/Riparian Habitat Working Group (1999: 10) who describe first order streams as "the least sensitive watercourses in terms of hydrological processes". The research undertaken by Daniels and Gilliam (1996: 251) produced similar contradictions, "(e)phemeral riparian channels need a continuous vegetative cover to be effective filters", a condition they note to be an impossibility beneath closed canopy forest.

3. DERIVING THE INDICES

3.1 SSI Derivation

In order to identify the sediment supply areas using the methods investigated, spatial modelling was undertaken using the Spatial Analyst extension of ArcView GIS (Version 3.2). The topographic analysis and application of two USLE-based erosion models, the RUSLE (Renard, Foster, Weesies & McCool 1991) and the flow accumulation method (Moore & Burch 1986) were automated using Avenue, the proprietary scripting language of ArcView Version 3. The factor requiring topographic analysis for both methods is the LS factor, a combination of the gradient and flow length associated with the terrain.

The RUSLE LS-factor (Renard, Foster, Weesies & McCool 1991) is derived using the following set of equations.

$$LS = L_s \cdot S_{sf} \tag{2}$$

Where

L_s = slope length factor

S_{sf} = slope steepness factor

And

$$L_s = \left(\frac{\lambda}{22.1} \right)^{m_{sl}} \tag{3}$$

Where

λ = flowlength

And

$$m_{sl} = \frac{\beta_r}{1 + \beta_r} \tag{4}$$

Where

$$\beta_r = \frac{\sin(S)}{0.0896\left[3.0(\sin(S))^{0.8} + 0.56\right]} \tag{5}$$

Where

S = gradient in degrees

And

$$S_{sf} = 10.8 \cdot \sin(S) + 0.03 \qquad \text{for } S_{\%} < 9\% \tag{6}$$

$$S_{sf} = 16.8 \cdot \sin(S) - 0.5 \qquad \text{for } S_{\%} \geq 9\% \tag{7}$$

$$S_{sf} = 3.0 \cdot (\sin(S)^{0.8}) + 0.56 \qquad \text{for } \lambda < 5\text{m} \tag{8}$$

Where

S = gradient in degrees

$S_{\%}$ = gradient in percent

As discussed earlier the application of the USLE requires that areas that are not sediment sources to be eliminated from the area of application. The method that was described earlier was applied using the following algorithm:

$$D = 0 \text{ if } (P_r curv < 0) \text{ and } (P_l curv < 0) \text{ and } (S < 5) \tag{9}$$

Else D = 1

Where

D = deposition areas

$P_r curv$ = profile curvature

$P_l curv$ = profile curvature

S = slope in degrees

Moore and Burch (1986) proposed a method of LS factor derivation that is based on unit stream power. Engel (1999) applied this method and derived the LS factor by combining the output of the flow accumulation model of ArcView Spatial Analyst with the gradient.

In order to derive the flow accumulation, the flow direction has to be established. The flow direction algorithm used in ArcInfo and ArcView is the D8 method, developed by Jenson and Domingue (1988), where flow is directed to from one pixel into one of its eight nearest neighbours. Flow accumulation is a count of the number of upslope cells that flow into the processing pixel (ESRI 1996). Moore and Wilson (1992) argued that the physically based LS-factor developed by Moore and Burch (1986) can account for complex slope geometries and describe soil transport by both sheet and rill flow, reducing observed inconsistencies in the result of USLE-based models.

The Moore & Burch (1986) LS factor is derived as follows:

$$LS = \left(\frac{al}{22.13}\right)^{0.4} \cdot \left(\frac{\sin S}{0.0896}\right)^{1.3} \tag{10}$$

Where

al	=	upstream contributing area
S	=	gradient in radians

Translated for application in GIS using raster data structures, the equation can be written as:

$$LS = \left(\frac{fa \cdot ca}{22.13}\right)^{0.4} \cdot \left(\frac{\sin S}{0.0896}\right)^{1.3} \tag{11}$$

Where

fa	=	results of flow accumulation algorithm
ca	=	area of raster cell
S	=	gradient in radians

Both methods of SSI derivation reveal a similar distribution of high-risk areas. It is claimed, though, that the flow accumulation can account for complex slope geometries and describe soil transport by both sheet and rill flow (Moore & Burch 1986). Additionally, this method is not dependent on the elimination of deposition areas prior to application. Consequently, the results of this method are used as the basis for further analysis.

3.2 DRI and SAI Derivation

3.2.1 Delivery Risk Index

The derivation of the five sub-factors for the Delivery Risk Index is presented below.

Road Stream Adjacency

Using the proximity function in ArcView Spatial Analyst it is possible to determine the Euclidean distance between features in a spatial dataset. The result of this analysis is a surface that is best described as a continuous buffer between features. The features themselves are assigned a value of one (1) in this analysis. The function was applied to the roads dataset and to the streams dataset, thus producing two continuous surfaces presenting the distance between the features within each dataset. By multiplying these surfaces together, and extracting values beneath a certain threshold it is possible to develop an index of road stream adjacency. Based on the findings regarding buffer width efficencies, a 10m to 20m buffer width should be adequate for sediment attenuation. The upper estimate is used for establishing a threshold for extracting road-stream adjacency areas. The reason for using the upper width limit was the need for a conservative assessment, given the generally mountainous terrain of the study area. This means that road-stream adjacency is defined by areas where the product of the two proximity datasets is less than or equal to 400 (20 multiplied by 20).

However, since the identification of the area is driven by the product of the sub-factors, any combination of values that results in a value lower than the threshold are accepted as valid areas of adjacency. This results in a dataset in which the entire road and stream features themselves, which are assigned a value of one, are included (1 multiplied by 1 < 400).

To overcome this problem, the areas where the product of the two Euclidean distance datasets was equal to one were eliminated. This however, resulted in areas that were not contiguous, divided by linear features the width of the analysis resolution, which arose from the removal of the road and stream features. These were eliminated by performing a focal statistical analysis, which assigned the maximum value within a 3 by 3 matrix to all cells within the matrix, across the study area. The areas identified as adjacent were assigned a value of ten and all other areas were assigned a value of one[2].

The algorithm for identifying areas of adjacency between roads and streams is:

$$RS_a = 10 \text{ if } (R_a \bullet S_a) \leq 400 \qquad (12)$$

$$RS_a = 1 \text{ if } (R_a \bullet S_a) > 400$$

Where

RS_a	=	Road stream adjacency index
R_a	=	Road adjacency
S_a	=	Stream adjacency

It should be noted that the actual risk is associated with areas where the stream is downslope of the road. The modelling results depicted above do not address this issue. However, the results are adequate for identifying general areas of risk in the landscape.

Proximity to road-stream crossings

Road-stream crossings (Hairsine 1998; Tennessee Department of Agriculture 1993) are areas of particularly high risk for sediment delivery to streams. These crossings can be identified using an intersect-overlay analysis routine in ArcView. This creates a point dataset depicting every road-stream crossing. The same proximity analysis as was performed in deriving the road-stream adjacency analysis, producing a surface of Euclidean distance between stream

[2] Zero cannot be assigned since it would result in the exclusion of most of the study area, when combining the sub-factors to produce the index.

crossings. This dataset can be classified to produce a value for the proximity to road-stream crossings sub-factor. The values for the sub-factor were assigned as presented in Table 3.

Table 3: Road-stream intersection proximity sub-factor

Proximity to intersection (m)	Intersection proximity value
0 – 10	10
10.1 – 20	7
20.1 – 100	2
> 100	1

The values are based on the assumption that the impact of the interaction between the roads and streams is driven by the proximity to the intersections between them. This relationship is assumed to be non-linear; features within the immediate surroundings of the crossings assumed to have greater potential to impact on the associated watercourse. The impact is assumed to be negligible beyond 100m from the crossing. As with the adjacency sub-factor, it is the upslope area from each crossing that is critical, although the utility of the results in identifying areas of concern is not undermined.

Road-surface condition

The road surface condition is a factor that cannot be modelled. Ideally, an in-field assessment of every road is required. This is extremely labour intensive given the high road density associated with South African plantations. There are, however, classification systems for roads that are used within the forestry industry, but these systems, although similar, are not standard across the industry. The road dataset used in the case study had the standard Sappi Forests classification applied. The class of the road had to be used as a proxy for surface condition. The road classification and associated risk value assigned to each class of road are presented in Table 4. The assumed risk values are based on the factors identified from the literature. Areas not occupied by road surface were assigned a value of one.

Table 4: Road surface condition sub-factor

Road class	Description	Risk	Value
A	Tarred road with proper drainage	Very low	1
B	Gravelled or unsealed road > 5m wide	Moderate	6
C	Unsealed road, 3-5m wide	Very high	10
D	Grassed track < 3m wide	Low	4

Road surface erodibility

The road surface erodibility is the most difficult sub-factor to model, although the actual model used is the same as for the Sediment Supply Index. One confounding aspect is that roads do not follow the morphology of the terrain they run through. This complicates the modelling of the slope and flow-length along the roads enormously. One cannot rely on standard terrain modelling to derive any of the sub-factors.

The first requirement is to develop a linear dataset that reflects the morphology of the road network. By intersecting the road network with a set of contours with a three-meter interval derived from the DEM, an elevation point dataset, sampled along the roads, can be developed. Attempts to produce a raster dataset, from this point dataset, where the interpolation was constrained by the known road width, proved unsuccessful. Processing times exceeding 96 hours, combined with unpredictable results, made this method unusable.

To overcome this nodes were created in the road dataset wherever the roads and 3m contours intersected. This produced a dataset of roads where there is a three-meter change in elevation along each road segment. Deriving the length for each segment was accomplished using the ArcView "shape.returnlength" request. This enabled the slope of each road segment to be calculated, since the run and the rise had been established. Additionally, the roads were intersected with the landtype/terrain unit polygons, effectively transferring the K-value from the landtype data to each road segment. This procedure does not account for the possibility that the road surface may be gravelled. To adequately address this issue would require a detailed set of attributes for each road length, which are not available in the standard road attributes maintained by the forestry industry, although they could be captured and maintained should they be regarded as important.

The resultant tabular dataset associated with the spatial road dataset was transferred to a spreadsheet (Microsoft Excel). In Excel the slope (%) was calculated. From this, slope in degrees was derived for each road segment. This angle was translated into radians for the application of the USLE (Eqn. 1). The LS subfactor derivation used was the Moore and Burch (1986) method based on unit stream power (Eqn. 10). The Excel spreadsheet was transferred back into ArcView and linked back to the spatial road dataset using the internal unique ID in the attribute table. The road network was converted into a raster dataset using the calculated topographic erosion potential as the value item. The values in the resultant grid were normalized to a score out of 10 and areas not occupied by the road surface were assigned a value of one. This procedure assumes all road surfaces in the dataset to be sediment-producing surfaces. This assumption would not be necessary if detailed road information was available.

Topographic delivery efficiency

This final sub-factor refers to the topographic characteristics of the terrain that may expedite sediment delivery to streams. Essentially, this identifies areas of convergent flow across the landscape. It is derived by extracting the negative values from the results of the planform curvature, derived using the curvature request in ArcView Spatial Analyst. All areas of convergent flow were assumed to provide topographic linkages between roads and streams, and were assigned a value of 10. All other areas were assigned a value of one.

Combining the sub-factors

The five sub-factors need to be combined in order to establish the overall delivery risk index. The index was derived by calculating the average value of all five sub-factors across the landscape. A sensitivity analysis was undertaken because, although each factor is an acknowledged contributor to the index, the impact of the interaction of the sub-factors is uncertain. The sensitivity analysis provided a way of assessing whether the priorities identified by the proposed method changed significantly with each scenario definition. Significant differences would be the identification of different hotspots that would result in a different management approach being adopted to manage erosion in the landscape. Three varying weighted overlay scenarios were undertaken which are defined in Table 5.

Table 5: Factor weightings (%) for Delivery Risk Index scenario definitions

	Intersection proximity	Road/stream adjacency	Delivery efficiency	Road surface condition	Road surface erodibility
Scenario 1	20	20	20	20	20
Scenario 2	20	30	30	10	10
Scenario 3	30	30	30	5	5

Scenario 1 is a baseline equal weighting overlay. In Scenario 2, road-stream adjacency and delivery efficiency have been weighted to account for 60% of the index. The remaining sub-factors, road surface condition and road surface erodibility, are assigned equal weighting. It is assumed, in this scenario, that convergent flows between roads and rivers, separated by a narrow corridor are significant factors in the delivery risk index. This is based on the observation in Australia of how watercourses become linked to streams by gully formation at the outlets of drainage structures (Furniss, Flanagan & McFadin 1999; Mockler & Croke 1999; Lamarche & Lettenmaier 2000). The actual sediment contribution of the gullies themselves have been excluded, since their existence is hypothetical. Scenario 3 was defined to minimize the impact of the datasets in which confidence is lowest, or have higher level of assumptions, on the final delivery risk index. Given the computational problems encountered in the development of the road surface erodibility sub-factor, and the assumptions regarding road class and the surface condition sub-factor, the weighting of each of these has been reduced to 5%. The results of the three scenarios differ in the distribution of the moderate to high categories. However, the spatial distribution of the higher risk categories is similar in all three scenarios, suggesting that all three would identify the same specific areas as hotspots in the landscape.

3.2.2 Sediment Attenuation Index

The gradient of the terrain is a contributing factor in identifying areas that may act as sediment sinks in the landscape. In the discussion of the SSI derivation, it was noted that gradients of less than 5%, are assumed to be deposition areas (Smithers & Schulze 1995). This same threshold is applied here as an indication of sediment attenuation potential.

Wetlands are more likely to form on areas of less extreme topography. The three datasets produced by the curvature analysis were reclassified to eliminate extreme terrain, where the terrain morphology is too rugged for wetland occurrence to be likely. A manual inspection of the datasets, and examination of the ranges of values informed the development of a classification scheme. Areas were classified as topographically suitable if the values representing convexity and concavity were less than 10% of the maximum values for these indices. Thus the limits of concavity and convexity, the negative and positive values in the results of the curvature analysis, were set to eliminate the areas where the value exceeded 10% of the maximum score.

The datasets resulting from the methods described in the above two paragraphs were added together to develop the SAI. Since many of the features identified were only a single cell in size, and consequently difficult to depict on a map, it was necessary to enlarge them. A focal maximum process, with a 3 by 3 matrix, was run on the dataset to improve the visibility of identified areas. Since the purpose of the index is to identify areas with sediment attenuation potential, rather than the accurate delineation of existing features, this final analytical process should not be regarded as a degradation of the analysis resolution, but rather as a necessary enhancement for cartographic purposes, given the size of the identified features.

3.3 Buffer width definition

Karssies and Prosser (2001) present a method for determining buffer width requirements, based on the mechanisms of sediment trapping within buffers. Although not developed specifically for forestry conditions it is the only known method for deriving buffer widths, based on topography and sediment supply that can be readily applied in a GIS environment. In its simplest form it can be presented by the equation below.

$$w = 2 + 0.636A - \frac{0.12}{\tan\theta} \tag{13}$$

Where

w	=	buffer width recommendation
A	=	annual soil loss ($t.ha^{-1}.yr^{-1}$)
θ	=	gradient (degrees)

The Sediment Supply Index provides a worst-case scenario for potential sediment supply. The index is not a quantitative measure of sediment supply but a measure of the potential erodibility based on soil and topographic factors only. Using the SSI will result in extremely wide buffer width recommendations. These recommendations, based on the SSI, would be exaggerated. It was therefore necessary to add the C-factor into the sediment supply derivation to develop a more realistic assessment of the actual amount of sediment produced. This does not undermine the utility of the original index in establishing priorities in the landscape; it only serves to enable realistic buffer width recommendations to be developed.

The C-factor was determined using the methods described by Smithers *et al*. (1995), which were developed for South African conditions. The unplanted areas were assumed to be grassland in moderate condition. Afforested areas were assumed to have a mulch layer of 25mm with a loose and friable soil texture (based on observation during the field trips). Smithers *et al.* (1995) provide a range of initial SCS curve numbers for different hydrological soil groupings and landcover classes. Based on the above assumptions an initial SCS curve number was determined for each combination of hydrological soil grouping and cover. This initial curve number was input into the equation for determining the C-factor based only on the initial SCS curve number, presented by Smithers *et al*. (1995).

These factors were incorporated into the erosion modelling procedures. The resultant dataset was used to determine the mean sediment supply (considering landcover) for each of the small catchments using the zonal-statistics functionality in ArcView Spatial Analyst. Mean slope per catchment was determined in the same way. This supplied the two inputs into the buffer width equation (Eqn. 13).

4. APPLICATION

Best practices for managing sediment delivery to streams exist within the forestry that address the issue during the three phases that have been identified. The results of the modelling procedures presented in this document can be used to develop integrated strategies for applying these management practices. An example of the application of the three indices, leading to the development of such a strategy is presented in the following four diagrams. The priority areas were identified by delineating areas generally at higher risk than the surrounding areas. This permits priorities to be established at a site-specific scale. The area depicted is a small section of the overall study area, selected for the fact that it represents a variety of conditions. The black numbers depict the compartment identifiers.

In the SSI (Figure 5) and DRI (Figure 6) maps, the scores have split into five descriptive classes based on the distribution of values with the datasets. Each class represents a doubling of the scores. The SAI is simply an indication of areas that are either suitable for sediment attenuation or not, represented by two classes in the map (Figure 7). Figure 8 presents an example of a site-specific sediment control strategy. Figure 9 depicts the recommended buffer widths, derived using the Karssies and Prosser (2002) method, for the mapped area.

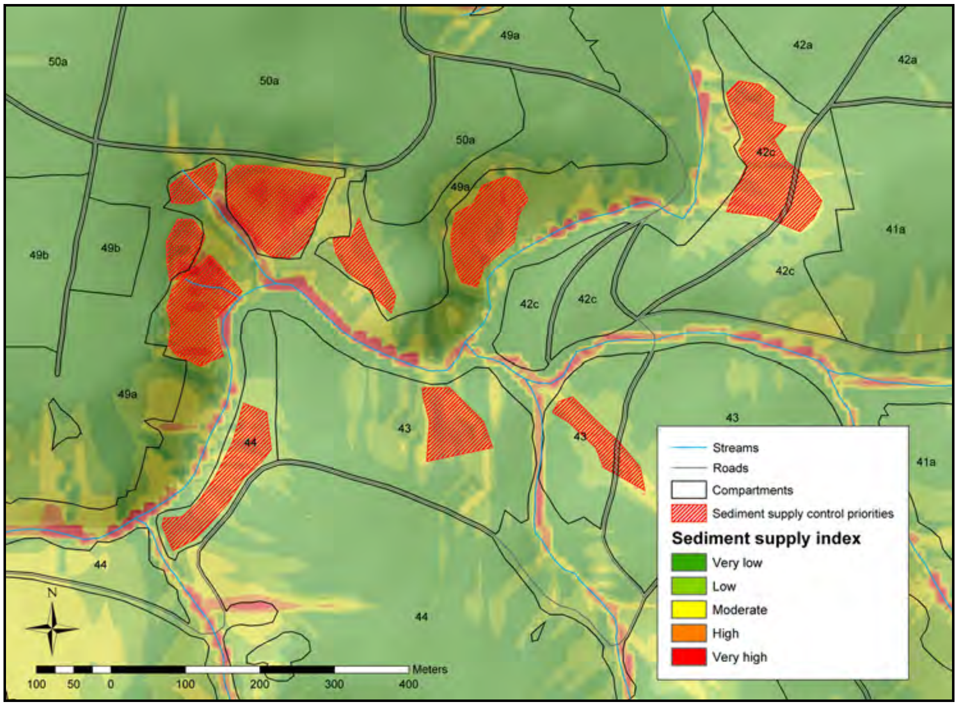

Figure 5: Priority areas for sediment supply control based on the Sediment Supply Index

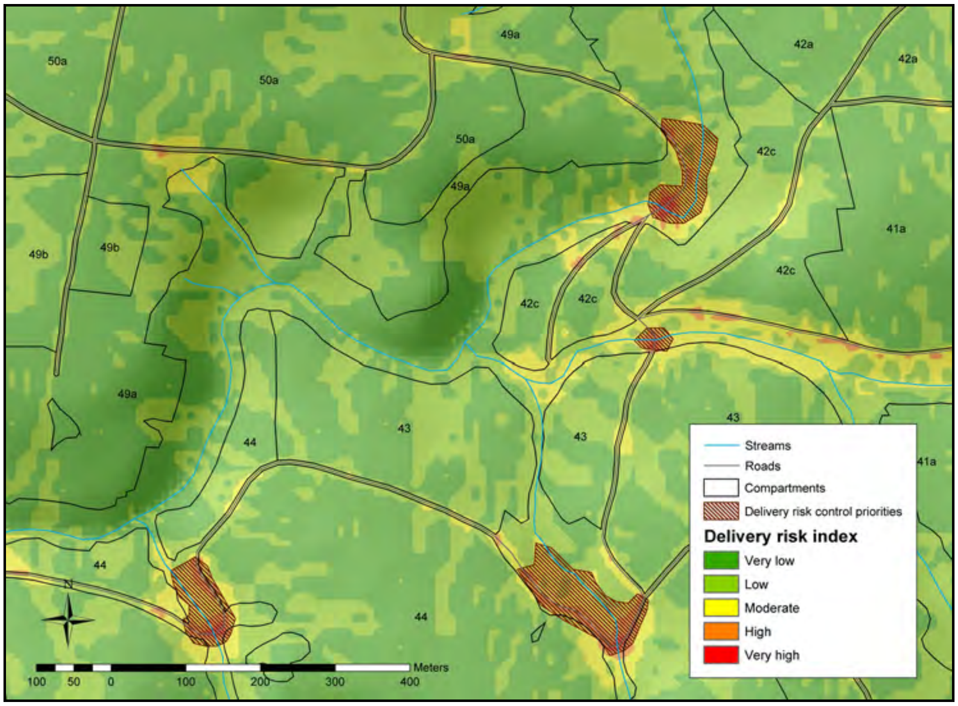

Figure 6: Sediment delivery control priorities based on the Delivery Risk Index

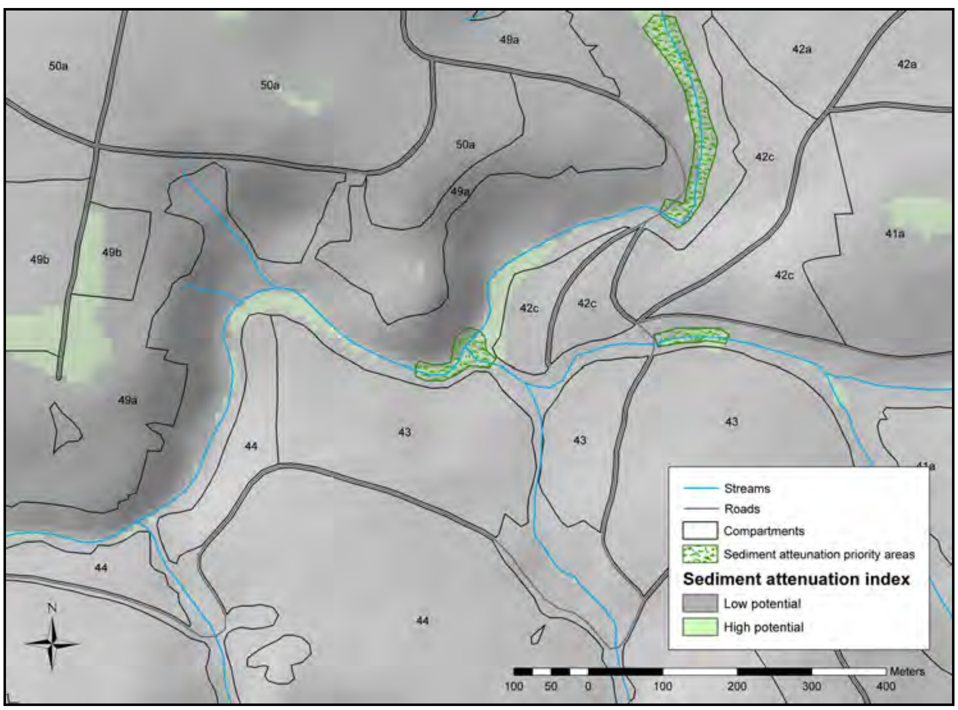

Figure 7: Potential sediment attenuation features identified using the Sediment Attenuaton Index

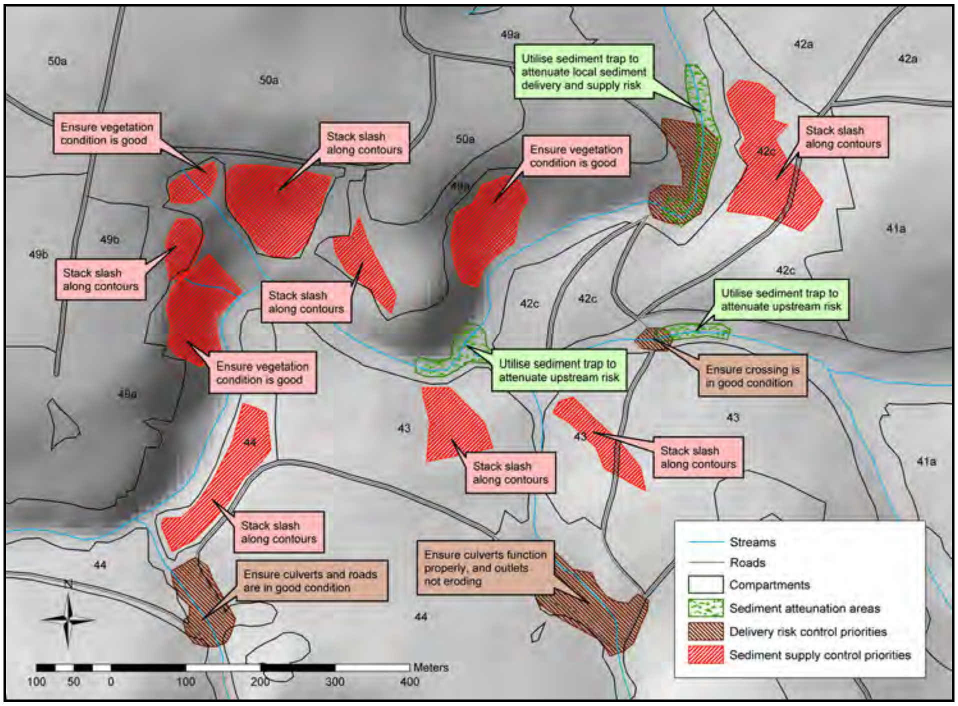

Figure 8: Example of an integrated sediment control strategy for the map area based on all three indices

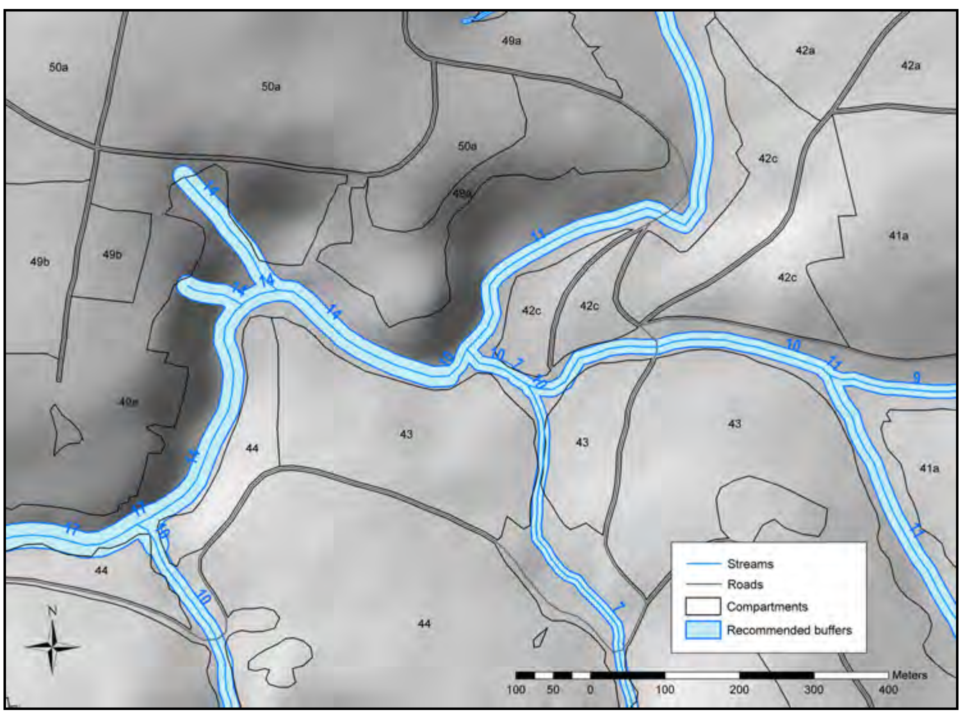

Figure 9: Buffer width recommendations as developed by applying the method of Karssies and Prosser (2002). The blue figures indicate the buffer width in meters.

5. CONCLUSIONS AND RECOMMENDATIONS

The current role of the forestry sector as an economic contributor is recognized, as well as its potential to contribute to the upliftment and economic empowerment of rural communities (DWAF 1995). However, there is a concomitant realization of the potential environmental impact of forestry activities. Particularly, the impact of commercial forestry on water quantity and quality is of concern in South Africa. Increasing public awareness of environmental issues is compelling industries to ensure that their activities are conducted in a responsible and sustainable manner. The research has attempted to contribute to the sustainable management of commercial forestry plantations by developing tools to identify priorities for erosion control. The results of the application of these tools can be used to make site-specific recommendations within the identified priority areas.

The results of the modelling undertaken correspond well to erosion observed during field trips and identified off aerial photographs. This suggests that the methods employed are suitable for identifying areas of high erosion potential, given the data constraints under which the procedure is likely to be applied. From the perspective of establishing management priorities the implementation of process-based models is unlikely to enhance significantly the results achieved using the simpler, empirical models.

The following section will present specific recommendations regarding each of the indices developed.

The Sediment Supply Index

- The effect of improved data resolution needs to be investigated. This should inform the future data collection strategies of the forestry industry. This consideration is particularly relevant to the development of USLE K factor.
- The assumptions of the method for identifying areas of low sediment mobility presented are functional, but tenuous. The relationship between the values of the results of the curvature analysis and the actual terrain need to be investigated.
- Further fieldwork to verify the results should be undertaken, for example mapping of observed soil erosion and topsoil loss surveys.

The Delivery Risk Index

- Generally, little research has been done on the interaction of the contributing factors, although the effects of each are fairly well known in isolation of one another. Research should be conducted to improve the understanding of the interaction between roads, streams and topography, and its effect on sediment delivery.

- Quantitative research will inform the process of assigning risk values to the sub-factors, which are currently based on assumptions derived from the literature, or coarse dualistic categories.
- An improved method for modelling road-surface needs to be developed. The objective would be to eliminate the road-facet bias of the method used in this study, in favour of a method that is based on topographically continuous road units.
- The assumptions made, in the light of the paucity of relevant data, relating road surface condition to road class need to be investigated.
- The thresholds used for establishing road-stream adjacency need enhancement. Incorporating the gradient of the landscape between the features, as well as the curvature of the terrain, will improve the derivation of this sub-factor.
- The inclusion of existing culverts into the process for assessing connectivity would improve the development of this index. Unfortunately these data are not readily available.

The sediment attenuation index

- The relationship between the values of the results of the curvature analysis and the actual terrain needs to be established more precisely.
- The method should be applied in an area where the contribution of the method for identifying areas of undefined flow may be assessed.
- The utility of the improved digital terrain analysis should be investigated.

Integration of the indices

- The assumptions for developing the streamside risk indices need verification.
- The utility of the buffer width determination routines for forestry conditions needs to be investigated.
- The application of improved digital terrain analysis methods would result in improved delineation of stream networks, which would in turn provide better information on which the streamside risk indices are based.
- The proposed method should be implemented in its entirety for a test site, and sediment delivery monitored over a period of time, to evaluate its utility.

The results of the research suggest that the application of spatial modelling procedures can assist in minimising sediment delivery to rivers. The application of the results, at both landscape and compartment levels, enable tactical and operational management strategies to be developed. As the approach was developed using readily available datasets, and with the operational needs of the industry as a departure point, it is hoped that this contribution in the pursuit of sustainable forestry is implemented.

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Economic analysis of the eradication and management of invasive alien vegetation in the Mhlatuze River Catchment (KwaZulu-Natal, South Africa)

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1. Introduction

Alien invasive vegetation threatens the functioning and existence of natural ecosystems in South Africa because many of these plants have no predators or competitors, allowing them to dominate the ecosystem which they inhabit. The rapid proliferation of this alien vegetation, ascribed to the increase in afforestation and changes in land use, has had significant adverse impacts on water resources, biodiversity and the stability as well as integrity of these ecosystems. Although eradicating alien invasive vegetation gives rise to a number of different benefits, this process entails enormous costs. Consequently, in order to establish the economic viability of alien plant eradication it is essential to analyse these costs as well as the benefits associated with eradication.

The Mhlatuze River Catchment, which is considered the most severely affected tertiary catchment in KwaZulu-Natal in terms of alien vegetation infestation, was selected as the focus of this study. Although the cost-benefit analysis (CBA) was conducted in a small area, its findings can be extended to regional, national or even global situations. At the very least, this analysis offers insight into the feasibility of alien plant eradication and ascertains whether or not this eradication is beneficial to both landowners and the broader society.

This paper reviews the literature pertaining to alien invasive vegetation and outlines the methods selected for valuing the impacts of its eradication. Based on the analysis of data generated by the study, the economic efficiency of the clearing process was established, and future actions required to manage invasive alien vegetation identified.

2. Theoretical framework

The prevalent attitude towards eradicating alien invasive vegetation among timber producers is one of apathy; most producers undertake sporadic clearing, rather than the rigorous removal and sustained management of alien plants. In order to uncover the economic rationale for these attitudes, it is helpful to consider the economic theory underlying project appraisals as well as sources of inefficiency which lead to market failure.

The Hicks-Kaldor criterion (i.e. accept any project which results in a potential Pareto improvement) is central to the theoretical justification of CBA in welfare economics and provides the rationale for selecting projects whose benefits outweigh their costs (Perkins, 1994:50). CBA is purely concerned with the **economic efficiency** of a project and whether or not this increases social welfare. Equity effects are thus ignored: the project decision does not depend on to whom the benefits and costs accrue, or on whether society considers the prevailing distribution of income to be desirable. Some CBA frameworks, for example that proposed by the World Bank, address this issue by advocating the use of distributional weights.

In the idealised world of perfect competition, the interaction of many profit-maximising producers and utility-maximising consumers gives rise to a Pareto-optimal situation, which is efficient. Under these circumstances, prices reflect marginal economic costs and the private and social optimums coincide (Munasinghe, 1993:1732). The existence of prices means that scarcity can be gauged through the market forces of demand and supply, which ensures the efficient allocation of society's scarce resources (Perkins, 1994:95).

In the real world, however, distortions ascribed to monopoly practices, external economies and diseconomies, or interventions in the market process culminate in market (or financial) prices for goods and services that do not fully reflect the marginal benefit of their consumption to society and which may diverge substantially from their true economic values or shadow prices (Munasinghe, 1993:1732). The failure of the market to price resources efficiently inevitably leads to their over-exploitation and/or inefficient utilisation. Consequently, an argument can be developed for government intervention.

An **externality** exists where the action of one economic agent affects the utility or production possibilities of another in way that is not reflected in the marketplace (Just *et* *al.*, 1982:269). Externalities are particularly relevant to this study, since those individuals not currently engaging in alien plant eradication produce more output than the socially optimal level and adversely affect the welfare of downstream users, who as a result of this inactivity produce less output than the social optimum.

In practice, the correction of such distortions is difficult, since many environmental effects (e.g. increased biodiversity) display public good aspects (i.e. non-rivalry and non-exclusiveness in consumption), and fail to be recorded by market price movements. This explains why environmental effects are often excluded from analyses. For purposes of this study, environmental goods and services are relevant both in carrying out the CBA of eradicating invasive alien plants as well as the resulting decision on project choice (Hanley and Spash, 1993:10). Thus, it is imperative to ensure that such effects are included and, where possible, quantified.

3. Impacts associated with alien invasive vegetation

The invasion of natural ecosystems by alien plants is a serious environmental problem that threatens the sustainable use of benefits derived from such ecosystems (van Wilgen *et al.*, forthcoming:2). Although alien invasive vegetation may have benefits, for example it may provide food for human consumption (e.g. guavas) or may have aesthetic beauty, substantial costs are associated with this vegetation. Adverse impacts include:

- Streamflow reduction;
- Loss of biodiversity (as well as ecosystem resilience);
- Increased costs of fire protection and damage in wildfires;
- Loss of potentially productive land;
- Loss of grazing potential and livestock production (DWAF, 2000:16).

4. Characteristics of the Mhlatuze Catchment

The study area comprises a total of 48 633 hectares, of which approximately eight *per cent* (3 767 hectares) is densely infested with invasive alien vegetation. This heavy infestation is ascribed to the establishment of plantations of alien species as well as changes in land use. The area is dominated by the agricultural, forestry and industrial sectors, all of which are important in terms of their contribution to the local economy and/or their employment of local people.

The Mhlatuze Catchment has been classified as 'water stressed', since more water has been allocated to users than is actually available (Versveld *et al.*, 2000:v). It is anticipated that this scenario will deteriorate in the future, due to increased demand as a result of population and economic growth as well as the launching of the Richards Bay SDI. Furthermore, this catchment is characterized by high levels of unemployment, with most people in the rural areas engaged in a subsistence lifestyle.

5. Methodology

A multidisciplinary approach was adopted to document the findings of this study due to the wide range of biological, economic and social implications associated with the eradication of invasive alien vegetation. Data were gleaned from an array of sources which included books, journals, reports and government as well as policy documents. The research area was visited on a number of occasions and formal in-depth interviews were conducted with experts, major stakeholders and WFW employees. The purpose of these interviews was to identify the most significant impacts and capture salient information concerning the actual costs and benefits associated with the eradication process. A total of thirteen stakeholders located in the study area and five experts were interviewed. In addition, thirty Working for Water (WFW) employees residing and working in the study area were interviewed in order to evaluate the social effects of alien plant eradication, and to establish the benefits received from the WFW Programme.

Based on the responses elicited and on the literature survey conducted, those impacts with the highest relative importance were identified. The impact parameters selected include: harvesting of alien vegetation, streamflow amount, biodiversity and fire control. Where possible, the values of impact parameters connected with the eradication process were quantified.

All the data generated from this process were used to compile the results section of the report, and based on the findings, suitable recommendations were formulated.

6. Results and discussion

Analysis of the results indicates that all the private farmers and other major stakeholders in the study region are engaged in some form of alien plant control. However, this clearing has been more rigorous on private farmland.

6.1 Costs associated with alien invasive plant eradication

Alien plant eradication costs are dependent on the control method adopted (mechanical, chemical or biological control), as well as on the stage and frequency of clearing. Individuals in the study area use mechanical as well as chemical control methods, and are responsible for the full costs connected with alien plant eradication, except where the WFW Programme is operating on the individual's land.

The costs associated with these control methods include capital, operating and maintenance costs as well as the costs of follow-up operations. Rehabilitation costs are excluded from this analysis, since it was evident from stakeholder responses that no individual had been engaged in such a process.

The total costs of eradicating alien invasive vegetation depend on the degree of infestation (the density of alien plant cover), the type and age of the invasive species, and ease of access to the area (Hosking and du Preez, 1999:445). The total costs associated with clearing alien plants over a ten-year period were elicited from stakeholders. It was estimated that on average sixty-five *per cent* of the total costs pertained to labour, whilst twenty-five and ten *per cent* were correlated to herbicide and other costs like hired equipment and transport. The average costs associated with the various phases of alien plant removal (refer to table 1) are based on the above categorisation and on the following assumptions:

- The average weighted daily wage rate for labourers was fixed at R25.00 per person.

- All stakeholders adopted the same control methods.
- Garlon was the only herbicide considered in this analysis, since it was found that over eighty-five per cent of stakeholders in the area used Garlon. The cost of Garlon is R142.00 per litre (PPRI, 2000:20).
- Four follow-up operations were required to ensure alien plant density declines to less than ten *per cent* cover (Goodall *pers comm.*).
- Each stage of eradication is initiated annually in order of sequence (refer to table 1).

Table 1: Total costs associated with eradicating alien invasive vegetation for different phases.

Stages of eradication	Labour cost (Rands/hectare)	Herbicide cost (Rands/hectare)	Other costs (Rands/hectare)	Total cost (Rands/hectare)
Initial eradication	R 1,300	R 500	R 200	R 2,000
First follow-up	R 494	R 190	R 76	R 760
Second follow-up	R 280	R 107	R 43	R 430
Third follow-up	R 156	R 60	R 24	R 240
Fourth follow-up	R 123	R 48	R 19	R 190
Maintenance	R 104	R 40	R 16	R 160

This table highlights that so long as regular (that is, at least annual) alien plant eradication is carried out, total costs associated with clearing will decline with each successive year up until the maintenance phase, where costs will stabilise. Using the total invaded area of 3 767ha in the study region and the costs referred to in the table above, it is instructive to depict the change in total costs associated with alien plant eradication over the ten-year lifespan of the project (refer to figure 1). **It must be noted that the total costs will only follow this given trend if each and every eradication phase is properly and effectively implemented.**

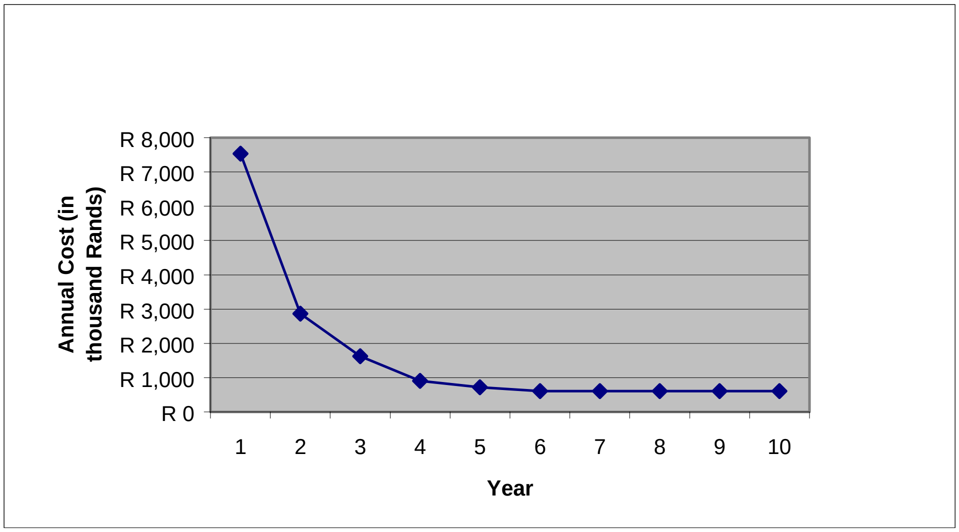

Figure 1: Total costs associated with eradication in the study area.

6.2 Benefit flow of alien vegetation eradication

It is necessary to distinguish between **private** and **social** benefits in this analysis, to establish the positive impacts of alien plant eradication and to highlight the distribution of these benefits. The ignorance of social benefits has given rise to the misallocation of resources in the past, and their inclusion in this analysis is thus a significant aspect of the study.

6.2.1 Private benefits

Private benefits are those accruing entirely to the proprietor, for example, income derived from the harvesting of alien vegetation and reduced fire management costs. Monetary values for such benefits are generally easy to derive from markets.

a) Utilisation of alien vegetation

The harvesting of alien vegetation is a **consumptive use value** that is dependent on the species eradicated, the relative age and the extent of infestation. From interviews conducted, it was apparent that the only alien invasive vegetation harvested were commercial timber species (*Eucalyptus*, *Pinus* and *Acacia mixed* species). Stakeholders estimated that on average, 20 tonnes of timber per densely invaded hectare were likely to be extracted in the initial phase of eradication. Further, they confirmed that there would be market demand for this additional timber at current prices. Thus to derive a monetary value for this vegetation, the extraction rate was multiplied by the profit per tonne (i.e. the market price less transport and processing costs) derived from the different timber species used for paper and pulp purposes, and summed (refer to table 2).

Table 2: Total value (August 2001 values) of commercial forestry species located in invaded areas of study area.

Commercial forestry species	Size of area[1] (hectares)	Tonnes of timber to be extracted[2] per hectare	Average profit per tonne[3] (Rands)	Total value (Rands)
Eucalyptus spp.	68	20	R200	R 272,000
Pinus spp.	26	20	R130	R 67,600
Acacia mixed spp.	1921	20	R290	R 11,141,800
TOTAL	**2015**	**-**	**-**	**R 11,481,400**

1-area occupied by harvestable commercial forestry species within the densely invaded area of the study region (i.e. 3767 hectares).
2- this is with reference to the **initial eradication phase** only.
3- average profit (i.e. net of costs) for specified commercial timber, which was derived from stakeholders in the study area (August 2001).

The value of harvesting alien vegetation in the initial phase of eradication in the study region amounts to R11 481 400 (refer to table 2). The largest proportion of this potential income will accrue from the harvesting and sale of *Acacia species*, which occupy fifty-one *per cent* of the total invaded area. This is based on the assumption that the entire invaded area is cleared in the first year.

b) Costs associated with burning

From questionnaires administered, it was estimated that the average cost of burning open grassland per hectare is R46/ha per annum. The presence of alien invasive vegetation increases this average cost to R74/ha per annum. Consequently, *ceteris paribus*, alien plant eradication would reduce fire hazard or management costs by the same proportion, that is R28/ha per annum or sixty *per cent*. In order to establish the annual reductions in fire management costs associated with alien plant eradication over the ten-year project period it was essential to examine the rate of recovery over time (i.e. establishment of indigenous vegetation). The following assumption was made:

- The expected rate of recovery over time will give rise to reductions in fire management costs of: 100% in the initial year, 95%, 90%, 85%, 70%, 60%, 50% and 45% in each successive year thereafter subsequent to alien plant eradication. Therefore, the maximum reduction in fire management costs occurs in year one, followed by small increments in costs up to the point where costs reach 55% of their pre-eradication levels (i.e. a sustainable saving of 45% of the base year costs).

Based on this assumption, the annual reduction in fire management costs in the study region was calculated. In the first year, provided that all alien vegetation is eradicated, these costs will decline by 100% or R 105 476. As indigenous vegetation establishes in cleared areas, the reduction in costs declines somewhat, as shown in figure 2.

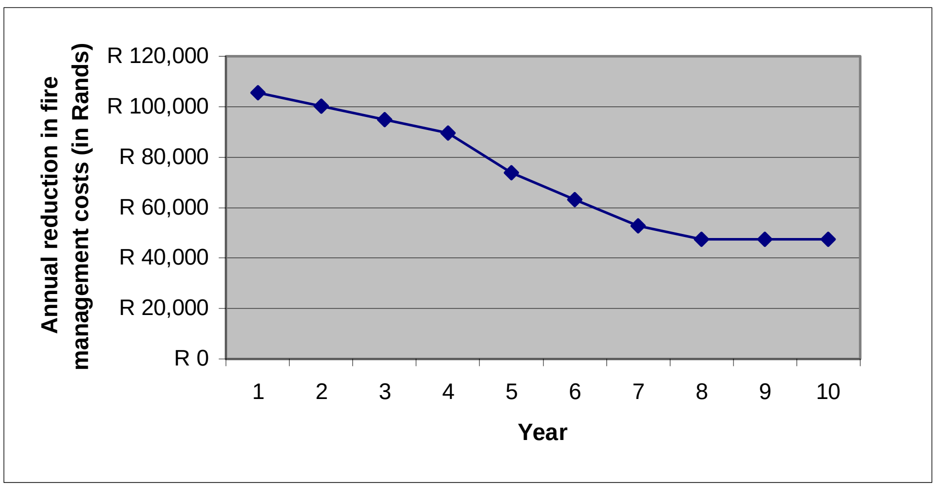

Figure 2: Annual reduction in fire management costs associated with the different stages of alien plant eradication for the ten-year project.

6.2.2 Social benefits

The social benefits flowing from alien plant eradication are those which accrue to society as a whole and include increased streamflow, increased biodiversity as well as employment benefits. It is important to incorporate these impacts into the analysis, and where possible quantify them, in order to prevent the misallocation of resources stemming from incorrect pricing information.

a) Streamflow increase

From previous studies, it is evident that streamflow reduction is positively related to vegetation biomass and age. Based on expert opinion, it was established that medium trees (which includes young *Acacia* and *Eucalyptus species*) dominate the invaded area of the study region, occupying over seventy *per cent* of the total invaded area (refer to Appendix I).

Using the data contained in Appendix I, streamflow reduction associated with the alien plants was calculated for riparian and non-riparian zones. The findings suggest that alien invasive vegetation in the study area reduces total streamflow by approximately 4.6 million m^3 per annum. Consequently, the eradication of this vegetation is expected to increase streamflow by the same amount. It is anticipated that only a portion of this increased streamflow will be reliably captured and extracted given existing infrastructure (Wood *pers comm.*). Based on catchment characteristics, experts predict that a minimum of fifty *per cent* of the increase in streamflow (about 2.3 million m^3 per annum) will be available for downstream use. In order to provide a more prudent appraisal, this conservative estimate was employed.

Using estimates of current water allocation in the catchment as well as the prices each sector is required to pay (refer to table 3), the total monetary value associated with increased streamflow per annum was calculated. It is estimated that if all alien vegetation were removed from the study area in the first year, the monetary value of increased streamflow would amount to R422 584 (refer to figure 4). This initial amount would be expected to decline somewhat over time, as indigenous vegetation reclaims the cleared areas.

Table 3: Current allocation of water and differential water tariffs sustained by sectors located in the Mhlatuze Catchment (van der Merwe *pers comm.*).

Sectors of water use	Current allocation of available water (%)	Current water price[1] (cents/m^3)
Irrigation sector	60	2.08
Domestic sector	14	42.34
Industrial sector	26	42.34

1- price includes infrastructure and catchment management charge.

Increased streamflow arising from eradicating alien invasive vegetation accrues to those individuals situated downstream from this clearing activity, which for purposes of this study includes rural communities, private farmers as well as industries. Increased streamflow is an example of a positive externality, in that it enhances society's welfare and downstream users are able to produce at their socially optimal output level. Because of the social nature of this benefit, private individuals generally fail to take it into account when allocating resources.

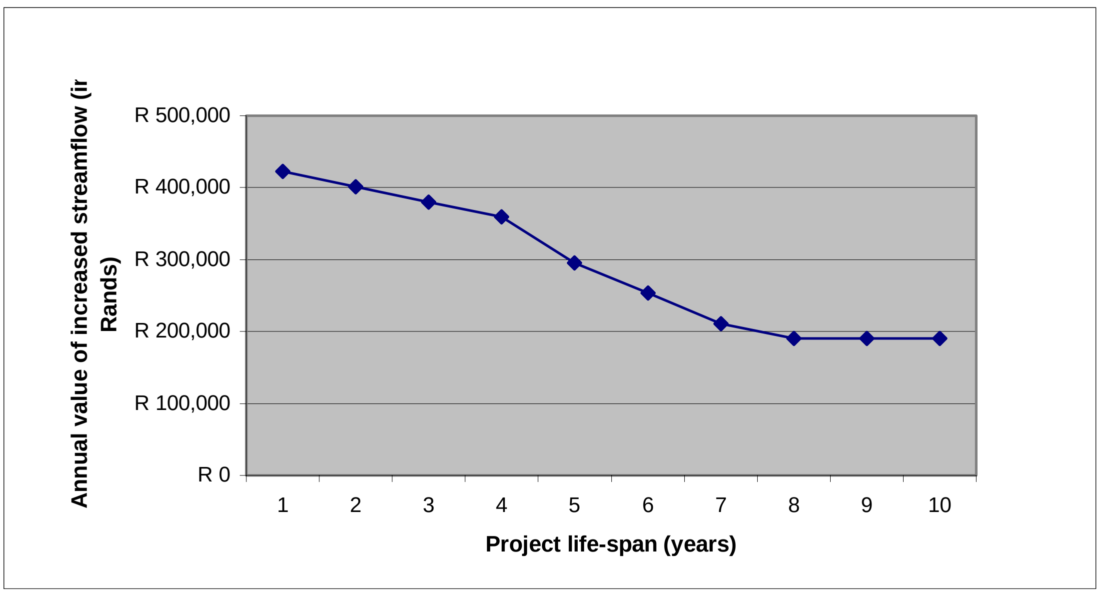

Figure 4: Annual value of the anticipated increase in streamflow over the project life span.

b) Increased biodiversity

Biodiversity is an important benefit flowing from the eradication of alien invasive vegetation. However, due to the complexity of critical ecosystem services and the public good aspects which biodiversity displays, it is difficult to measure and value. Techniques such as the contingent valuation method (CVM) have been developed to assign monetary values to such goods. The CVM uses surveys of expressed preferences to establish willingness to pay (and thus, demand) for the good in question. This method was employed in the present study in an effort to derive the demand for biodiversity. Eighty-five *per cent* of the stakeholders in the study area asserted that biodiversity was important and was a benefit associated with alien plant eradication. However, when these stakeholders were questioned directly about their willingness to pay (WTP) for an increase in biodiversity, all respondents stated zero WTP, which apparently contradicts their earlier responses.

There are several probable explanations for this atypical behaviour. First, such a non-compensatory stance can be viewed as evidence of a lexicographic preference. Individuals may express no WTP for increased biodiversity as a protest against the implication that it could be traded for other goods or money. Secondly, individuals may have experienced problems in comprehending the concept of biodiversity and/or the benefits that would accrue from an increase in biodiversity. Thirdly, individuals may be uncertain as to whether eradicating alien plants will give rise to increased biodiversity, since a change in the biodiversity level is often difficult to assess and/or demonstrate. (It is possible that the latter two problems may have persisted, despite efforts made during the interview process to ensure that respondents understood and accepted the concept of increased biodiversity.) Finally, biodiversity has public good characteristics and thus individuals may attempt to 'free ride', expressing no WTP for the good and concealing their true preferences in the expectation that others will sustain the cost.

Given the inherent uncertainties regarding the increase in biodiversity, rather than attempting to assign a monetary value to this benefit, it was considered more prudent to assert only that all biodiversity is valuable as a resource, and any increase therein as a result of alien plant removal would be socially desirable.

c) Employment benefits

Although the employment of individuals is essentially a cost associated with alien plant eradication, when such employment enhances the welfare of society through reduced poverty and crime levels it may also be regarded as a social benefit. It has been established that the Mhlatuze Catchment is characterised by high levels of poverty and unemployment, which have contributed to the escalation of crime and violence. Job creation arising from alien plant removal in the catchment is likely to enhance living standards and social stability in the area, and is thus of paramount importance. External social benefits of employment were not quantitatively defined in this analysis, but are highlighted here as an important additional benefit.

The magnitude of this employment benefit is contingent upon the number of labourers employed, which in turn depends on the form of alien plant control adopted. Where mechanical and chemical control methods are used, employment benefits are large – e.g. between 4 and 60 labour days are prescribed for the initial eradication of one hectare of densely invaded land (de Wit and Crookes, 2000:41). Bio-control methods do not compare favourably in terms of employment benefits.

Finally, it is noted that WFW Programmes could potentially provide additional benefits, such as extensive skills training. However, in the study area such benefits were not recorded.

6.2.3 Cost-benefit analysis

The cost and benefit flows identified above occur at different stages of alien plant eradication as well as in different years. In order to compare these flows it was essential to convert them into common units such as present values determined by the discounting process. The average real interest rate on long-term bonds in South Africa over the last ten years was used to define an appropriate discount rate for this project, which was five *per cent*. Using this discount rate, the eradication of alien vegetation in the study area would realise a Net Present Value (NPV) of R4 047 703 over ten years (refer to table 4).

Table 4: Cost and benefit flows associated with alien plant eradication in the study area.

Year	Total benefits (in Rands)	Final cost (in Rands)	Net benefit or cost	NPV Discount rate 0%	NPV Discount rate 5%	NPV Discount rate 10%
0	R 12,009,460	R 7,534,000	R 4,475,460			
1	R 501,657	R 2,862,920	R -2,361,263			
2	R 475,254	R 1,619,810	R -1,144,556			
3	R 448,851	R 904,080	R -455,229			
4	R 369,642	R 715,730	R -346,088			
5	R 316,836	R 602,720	R -285,884			
6	R 264,030	R 602,720	R -338,690			
7	R 237,627	R 602,720	R -365,093			
8	R 237,627	R 602,720	R -365,093			
9	R 237,627	R 602,720	R -365,093			
TOTAL	-	-	-	**R -1,551,529**	**R 4,047,703**	**R 4,250,973**

In order to test the sensitivity of the NPV result obtained to the discount rate, rates of zero and ten *per cent* (i.e. one standard deviation on either side of the discount rate selected) were also applied. From table 4 it is apparent that the NPV is very sensitive to the choice of discount rate. When the discount rate is zero *per cent,* which means that future cost and benefit flows are not actually discounted, the NPV amounts to –R1 551 529 over ten years. Under these circumstances alien plant eradication would be undesirable and rejected. However, a five *per cent* increment in the discount rate from zero to five *per cent*, is accompanied by a R5 599 232 increase in the NPV. In contrast, when the discount rate is increased from five to ten *per cent,* NPV increases by only R203 270, to R4 250 973. The cause of these changes can be investigated by examining the cost and benefit flows associated with alien plant eradication over the ten-year period.

Although the total costs associated with the eradication of alien plants decrease with time, these are still substantial over the ten-year lifespan of the project when compared with the benefits. For all years except the current year (in which the eradication effort is assumed to be initiated), the costs of eradication outweigh the benefits. In other words, sizeable net costs (i.e. negative net benefits) are recorded for years 1 to 9. The higher the discount rate employed, the lower the importance of more distant cost and benefit flows today. Thus, large net costs that stretch into the future will be substantially reduced when a high discount rate is employed, making the alien plant eradication process more desirable.

On the other hand, the largest of the quantified benefits of eradication are realised in the base year, and are not subject to discounting (because the immediate benefits from timber sales, the initial streamflow increase and reduced fire management costs are experienced as soon as clearing is undertaken). The use of a higher discount rate therefore does not affect the benefits to the same extent as the costs associated with alien plant clearing. This explains the high NPV obtained when a positive discount rate is used.

A sensitivity analysis was also performed on those variables with low confidence estimates to ascertain the effects of these on the NPV outcome. Estimates of confidence levels were based on the researcher's and expert opinion. Those assumptions with the lowest confidence estimates include increased water availability, and the water prices different sectors will be required to pay in the future. An increase in the available streamflow from 2.3 million m^3 to 3.7 million m^3 per year was investigated. Furthermore, an increase in the water tariff charged to the irrigation sector was postulated. The effects of both of these on the NPV outcome were found to be largely insignificant, and it can be concluded that the final NPV is relatively insensitive to changes in these variables.

Examination of the findings presented above indicates that the NPV outcome is dominated by the revenue obtained from harvesting alien vegetation, and the eradication costs. It is surmised that the final outcome will be sensitive to substantial changes in these components. All other impacts play a relatively minor role.

In summary, the CBA indicates that removing alien plants in the study area is economically viable as well as socially desirable when a discount rate of five *per cent* is employed. Further enhancing the argument in favour of extirpation, is recognition that the CBA undertaken for purposes of this study only examined some of the benefits associated with this project, and hence represents a minimum estimate of the benefits.

6.2.4 Distribution of costs and benefits

Cost-benefit analysis *per se* is only concerned with the economic efficiency of a project and hence, assumes that everyone has the same marginal utility of income. Essentially this means that gains and losses, to whomsoever they accrue, are given an equal ranking in the evaluation process. This provides the rationale for selecting projects whose benefits outweigh the costs, even if those individuals who gain from a project are not the same as those who pay for it (Perkins, 1994:55). This may result in accepting projects that are inequitable. Since policy decisions concerning alien plant eradication are the preserve of the politician, it is necessary to examine the distribution of costs and benefits, because a project which is efficient may nevertheless be undesirable if this distribution is highly skewed.

The costs and benefits associated with eradication in the study area are not proportionally distributed. In the absence of the WFW Programme and/or biological control, those individuals engaged in alien plant eradication sustain the full costs associated with this process. Although these individuals do obtain some financial gain from the commercial alien vegetation harvested and the curtailment of fire management costs, many of the benefits affiliated to eradication accrue to society in general. For example, downstream individuals can obtain monetary gain from utilising the increased water availability to augment production and furthermore, can enjoy positive effects such as increased biodiversity accruing from alien plant eradication. Consequently, there is a definite conflict of interests which prevails, as those individuals engaged in alien plant eradication must sustain the total costs associated with clearing, whilst all groups of society can essentially benefit from this clearing.

Profit-maximising individuals typically make decisions based on market prices and only consider the private costs and benefits related to a particular project when allocating resources. Consequently, such individuals are likely to engage in alien plant eradication for the initial year only, because private benefits exceed the private costs incurred in that year only (refer to table 4). Thereafter this outcome is reversed and private costs outweigh private benefits for all subsequent years. This leads to the prediction that individuals will discontinue alien plant eradication until such time as there is a monetary incentive to continue. Such a prediction is substantiated by sporadic alien plant eradication patterns recorded at a national scale. Sporadic clearing is inefficient in the long run, since alien vegetation is never under ‘proper’ control and hence alien plant density is never reduced. Thus, so long as individuals do not embark on regular clearing of alien plants, they will repeatedly have to face the initial, high costs associated with clearing alien plants. In order to encourage individuals to clear invasive alien plants from their properties, government policy intervention is required.

7. Conclusions and Recommendations

The issue is not whether to undertake control operations to remove alien invasive plants, but rather how to plan and execute sustainable control operations to ensure that the resources allocated to this activity are used as effectively as possible. Greater policy emphasis on and funds for curtailing widespread invasion by alien plants in South Africa are required in order to correct for the inefficiency associated with sporadic clearing.

7.1 Removal of externalities

The lack of alien plant eradication is an example of a negative externality which imposes costs on downstream users and is a result of the marginal private costs (MPC) consistently falling short of the marginal social costs (MSC) borne by society. In order to ensure the efficient allocation of resources it is necessary to close the gap between MPC and MSC. There are two appropriate strategies which may be adopted by government to internalise these costs namely, the introduction of a tax or a subsidy. Before these two measures are discussed it is essential to consider the socially optimal level of alien invasive plants.

7.1.1 Definition of the optimal alien plant level

Eradication of alien plants is economically worthwhile as long as the costs of clearing are outweighed by the (total) benefits. Thus, although this study has posited the complete eradication of alien plants in the study area, as a general point it should be noted that the optimal level of infestation in any given area is not necessarily zero. Rather, the socially optimal level of alien invasive plants is site-specific as well as species dependent, since site and species characteristics will impact on both costs and benefits of clearing. Policy-makers would need to take this into consideration in trying to define an appropriate level of a tax or subsidy to correct for the prevailing distortion in output levels.

7.1.2 Levying of a tax

Government can either levy a tax on individuals who are currently **not engaged** in alien plant clearing or alternatively, on those individuals engaged in **sporadic clearing**. It is important to ensure that the tax imposed for non-eradication exceeds the MPC of clearing, since only in this event will such a charge be effective in inducing individuals to remove alien plants in the long-term. Furthermore, the tax levied must be site-specific and charged per dense hectare of invaded alien plants.

7.1.3 Introduction of a subsidy

Government can subsidise those individuals that have been engaged in alien plant clearing on their properties. Subsidisation of those individuals currently engaged in clearing can be in the form of either monetary incentives or subsidising of certain costs (besides labour) incurred in clearing (e.g. herbicides). The subsidy, like the tax, should be site-specific and paid per dense hectare of invaded alien plants cleared. Subsidisation of costs or monetary measures require on-going monitoring by government officials to ensure that the resources provided are being used for the appropriate purposes.

7.2 Supplementary measures

7.2.1 Fire insurance premiums

The fire insurance premium is one measure which could be used to encourage private individuals and companies to engage in regular alien invasive plant clearing. Where individuals have removed or are in the process of removing alien plants from their land, their fire insurance premiums should be reduced because the spread of fire is much easier to control. Similarly, fire insurance premiums should be augmented where individuals have not attempted to eradicate alien invasive plants from their properties. The change in fire insurance premiums proposed will act as an **incentive** for individuals to engage in alien invasive plant clearing.

7.2.2 Formulation of a weed management plan

All those individuals owning large areas of natural land which are prone to alien plant invasion should be encouraged by government to formulate a **weed management plan**. This plan would entail the establishment of benchmarks which can be used to measure trends and progress towards achieving some reduced level of alien plant infestation. Such a plan is an important means of communicating information about progress towards goals set. The formulation of this plan might be encouraged by only offering subsidies to those individuals who have formulated weed management plans.

7.2.3 Improvements of alien plant clearing programmes

Programmes such as the WFW Programme are to be encouraged due to their potential for creating employment and thus alleviating crime and poverty, which is an extremely important aspect in a cash-strapped country facing massive unemployment. Based on criticisms raised by stakeholders in the study area, the following improvements to the current programme are proposed:

- To prevent animosity between stakeholders in the Mhlatuze River Catchment, it is recommended that the WFW Programme be **confined to state land** in the future.
- Stricter control of the current WFW Programme is required to reduce the number of conflicts between farm and WFW employees.

- Employment created by the WFW Programme *per se* is not a sustainable solution to the unemployment situation and it is therefore essential that WFW employees are taught skills which they can apply in other activities subsequent to the termination of the WFW Programme.

7.3 Further research required

7.3.1 Impact of alien vegetation on water

More research into the impact of alien invasive vegetation on the total available water is required. This will assist in ascertaining the actual volume of water which could in future be reliably captured and extracted for direct use, subsequent to clearing alien invasive plants. In addition, it is necessary to compare the costs of alien plant eradication to alternative schemes (e.g. dam construction) which will augment water resources in the Mhlatuze Catchment. This is important to ascertain and will indicate which are the most cost-effective in the long-term.

7.3.2 Formulation of bio-control agents

Continued research into the formulation of bio-control agents is required. This is important, especially since their development is likely to substantially reduce the future costs that individuals will have to sustain to effectively control alien infestations.

7.4 Concluding remarks

The major conclusion of this research is that there are many reasons why the eradication of alien plants is economically and socially desirable, both in terms of the efficiency and equity criteria that are generally accepted desiderata in progressive societies. The cost-benefit data for the Mhlatuze Catchment certainly suggest that alien plant eradication should be promoted in this area. It should, however, be noted that the costs and benefits presented in this study are site-specific and dependent on the type and density of alien vegetation, and that caution should be exercised in extending these conclusions to other areas.

Furthermore, the strategic planning of alien plant clearing initiatives is critically important, given the cost of such an exercise, and thus should also be promoted by government. It follows, therefore that policy-makers should identify policies or management options that are efficient and flexible, and hence can be applied to different areas where different characteristics pertain.

<u>Appendix I:</u> Average areas and age class of the alien vegetation located within and outside riparian zones in the study area.

The total dense area of invasive alien vegetation (i.e. 3 767ha) was divided into riparian zones **(i.e. eighty *per cent* or 3 014 ha) and** other zones **(i.e. twenty *per cent* or 753 ha).**

<u>Table 1:</u> Area and average age class of alien vegetation <u>in riparian zones</u>

	W12A	**W12B**	**W12C**	**Average (W12A,B&C)**
Area under **class 1** (tall **alien shrubs**)	11%	39%	34%	**28%**
Area under **class 2** (**medium trees**)	89%	56%	66%	**70%**
Area under **class 3** (tall **alien trees**)		5%		**2%**
Average age **class 1** (tall **alien shrubs**)	2 years	2 years	2 years	**2 years**
Average age **class 2** (**medium trees**)	5 years	5 years	5 years	**5 years**
Average age **class 3** (tall **alien trees**)		15 years		**15 years**

<u>Table 2:</u> Area and average age class of alien vegetation <u>outside riparian zones</u>

	W12A	**W12B**	**W12C**	**Average (W12A,B&C)**
Area under **class 1** (tall **alien shrubs**)	3%	24%	20%	**15%**
Area under **class 2** (**medium trees**)	97%	69%	80%	**82%**
Area under **class 3** (tall **alien trees**)		7%		**3%**
Average age **class 1** (tall **alien shrubs**)	2 years	2 years	2 years	**2 years**
Average age **class 2** (**medium trees**)	6 years	6 years	6 years	**6 years**
Average age **class 3** (tall **alien trees**)		15 years		**15 years**

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