AN EVALUATION OF THE SPATIAL VARIABILITY OF SEDIMENT SOURCES ALONG THE BANKS OF THE MODDER RIVER, FREE STATE PROVINCE, SOUTH AFRICA

By

Raboroko David Tsokeli

Submitted in fulfilment of the requirements for the degree of
Master of Science in Geography

Department of Geography
Faculty of Natural and Agricultural Sciences

University of the Free State
Bloemfontein

May 2005

Supervisor: Dr CH Barker

DECLARATION

I hereby declare that this dissertation is my own work and, to the best of my knowledge, contains no work submitted previously as a dissertation or thesis for any degree at any other university. I furthermore cede copyright of the dissertation to the University of the Free State.

Signed

Raboroko David Tsokeli

ABSTRACT

An evaluation of the spatial variability of sediment sources along the banks of the Modder River, Free State Province, South Africa.

(MSc dissertation by RD Tsokeli)

The study focuses on the characteristics of the Modder River in the Free State. The Modder River plays an important role in supplying water for domestic, agricultural and industrial uses in the Bloemfontein, Botshabelo and Thaba Nchu areas. According to present (2001) estimates by the Centre of Environmental Management of the University of the Free State, the Modder River is exploited to its full capacity owing to the construction of dams.

As the name of river suggests, the Modder River is said to have high sediment loads. In Afrikaans, *modder* means *mud*. The drainage pattern of the Modder River reveals well-developed dendritic drainage on the eastern part of the catchment and an endoreic drainage pattern on the western part.

This study aims to evaluate the spatial variability of sediment sources along the main course of the Modder River as well as assess the possible role of fluvial geomorphology in river management. The study is based on the hypothesis that the high sediment load in the Modder River main course is caused more by riverbank processes than by the surface of the basin. Helicopter and fieldwork surveys were carried out in order to obtain the required materials (variables). The spatial variability of bank-forming material, vegetation cover, type and channel form were investigated in order to realise the aim of this study.

The channel form of the Modder River indicates a decrease in sediment loads since the channel form shows some shrinkage immediately below the Krugersdrift Dam. The Modder River transports less and less sediments downstream as a result of a high number of constructed dams. Dams are barriers that create discontinuities in the channel system.

Observations of the characteristics of the banks of the Modder River reveal that these banks are resistant to erosion owing to the luxuriant vegetation growth and low stream power because of the channel gradient.

A question arises as to whether the Modder River really has such high sediment loads as its name suggests. Given the current state of the Modder River, high sediments are highly localised at certain sections of the stream. The transfer of sediments from one part of the river to another depends on the availability of sediment sources in space and time.

Keywords: Fluvial geomorphology; river engineering; sediment sources; bank erosion; bank stability; riparian vegetation; Modder River; impoundments.

ABSTRAK

`n Evaluering van die ruimtelike veranderlikheid in sedimentbronne langs die walle van die Modderrivier, Vrystaat Provinsie, Suid-Afrika.

(MSc verhandeling deur RD Tsokeli)

Die studie fokus op die karaktereienskappe van die Modderrivier in die Vrystaat Provinsie. Die Modderrivier speel ‘n belangrike rol in die watervoorsiening vir huishoudelike, landboukundige en industriële gebruik in die Bloemfontein, Botshabelo en Thaba-Nchu gebiede. Volgens die huidige (2001) skattings deur die Sentrum vir Omgewingsbestuur van die Universiteit van die Vrystaat, word die Modderrivier ten volle benut as gevolg van die oprigting van damme.

Soos die naam van die rivier aandui dra die Modderrivier ‘n hoë sedimentlading. Die dreineringspatroon van die Modderrivier getuig van ‘n goed-ontwikkelde dendritiese dreinering aan die oostekant van die opvanggebied en ‘n endoreïse dreineringspatroon aan die westekant.

Die doel van hierdie studie is om die ruimtelike veranderlikheid van sedimentbronne langs die hoofloop van die Modderrivier te evalueer, asook om die rol wat fluviale geomorfologie in rivierbestuur kan speel, te evalueer. Die studie is gebaseer op die hipotese dat die hoë sedimentlading in die Modderrivier se hoofloop eerder deur die rivierwalprosesse as deur die bodemoppervlak veroorsaak word. Helikopter- en veldopnames is onderneem om die nodige inligting (veranderlikes) te bekom. Die ruimtelike veranderlikheid van oewervormende materiaal, plantbedekking en soort sowel as vorm van die kanaal is ondersoek om die doel van die studie te bereik.

Die kanaalvorm van die Modderrivier dui ‘n afname in sedimentlading aan aangesien die kanaalvorm effense krimping wys direk onder die Krugersdrifdam. Die Modderrivier vervoer al hoe minder sediment stroomaf as gevolg van ‘n groter aantal geboude damme. Damme is versperrings wat onderbrekings in die kanaalsisteem veroorsaak.

Waarnemings van die eienskappe van die walle van die Modderrivier wys uit dat hierdie walle weerstandig is vir erosie as gevolg van die welige plantegroei en lae stroomkrag as gevolg van die kanaalhelling.

Die volgende vraag kan met reg gevra word: “Het die Modderrivier werklik hoë sedimentladings soos sy naam aandui?” Die huidige stand van die Modderrivier is dat hoë sedimentladings uiters gelokaliseer is en beperk is tot sekere dele van die stroom. Die oordrag van sediment van een deel van die rivier tot ‘n ander is afhanklik van die beskikbaarheid van sedimentbronne in ruimte en tyd.

Sleutelwoorde: Fluviale geomorfologie; rivieringenieurswese; sedimentbronne; oewererosie; oewerstabiliteit; oewerplantegroei; Modderrivier; opdamming.

DEDICATION

This work is dedicated to my late father, Mr Sechaba Tsokeli, and my mother Mrs MaRaboroko Mamalile, my brother; Pheello and my sister Masechaba Tsokeli, without whose emotional and financial support I would not be where I am today.

I also fondly remember my son, Phomolo (Hlompho).

ACKNOWLEDGEMENTS

I wish to express my sincere appreciation to the following:

- Almighty God for the strength and courage He gave me to carry on with my studies and to complete this research.
- The staff of the Department of Geography, University of the Free State (UFS), for their guidance in the course of this research.
- My special thanks to my supervisor, Dr CH Barker, for his support and guidance.
- The UFS Centre for Environmental Management for providing funding for this research. Without its financial assistance for this research (transport and sediment size analysis), the knowledge I acquired from this particular study in Fluvial Geomorphology would not have been as effective.
- My family, especially my mother, for believing in me and for making it possible to carry on with my studies.
- My best wishes to my brother and sister for their studies.
- My gratitude and good wishes to my colleagues, especially my close friend, Ngali.
- Prof Venter at the Unit for the Development of Rhetorical and Academic Writing.
- Louise for editing my work and Mrs Cronjé for translating the abstract.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

LIST OF PLATES

CHAPTER 1

AIM, RATIONALE AND METHODS

INTRODUCTION

The main part of the Modder River flows in the southern region of the central Free State Province with a minor part in the Northern Cape. The Modder River catchment covers a surface area of approximately 17 360km^2 (Midgley, Pitman and Middleton, 1994a), between 28°15' and 29°45' South and 24°30' and 27°00' East. The Modder River plays an important role in water supply to domestic, agricultural and industrial use in the Bloemfontein, Botshabelo and Thaba N'chu areas. In Afrikaans, *modder* means *mud* (Raper, 1987:223), indicating that the Modder River has high sediment loads, as its name, *Mud River*, suggests.

1.1 AIM OF RESEARCH AND HYPOTHESIS

1.1.1 Aim

This study aims to evaluate the spatial variability of sediment sources along the main course of the Modder River as well as to assess the role that fluvial geomorphology can play in river management.

1.1.2 Hypothesis

It is hypothesised that the high sediment load in the Modder River main course is caused more by the riverbank processes than by the surface of the basin (Barker, 2002:186).

1.1.3 Specific objectives

To achieve this aim and investigate the hypothesis, the following specific objectives were identified:

1. To index the type of sediments being transported through the channel and the resistance of the banks to erosion on twenty-one sites along the Modder River;
2. To determine the density of riparian vegetation, gullies and bank erosion, as well as impoundments on 5km segments along the Modder River;

3. To integrate various characteristics of the Modder River channel to evaluate the spatial variability of sediment sources, sediment transfer and bank stability; and
4. To pinpoint areas of bank instability and flood risk, as well as to assess their physical impacts on the Modder River.

1.2 PROBLEM STATEMENT

With an ever-increasing emphasis on alluvial channel systems worldwide through the continuing encroachment of urban areas and roads, a need exists for the assessment of channel conditions and the relative sensitivity of channels to disturbance or altered environmental conditions (Simon and Downs, 1995:216).

Evaluating the present channel forms and characteristics can lead to the identification of fluvial processes and resulting forms for the future. In this way, attention can be focused on those reaches that are likely to have the greatest adverse effects on bridges and on the land adjacent to the channels (Simon and Downs, 1995:216). More detailed analyses can then be undertaken along these reaches to plan and implement maintenance or mitigation measures to reduce economic and environmental risk associated with the channel instability.

The ecological health of rivers and wetland systems in the Free State is not well documented (Seaman, Roos and Watson, 2001). The sediment sources along the Modder River especially have never been determined in detail. These rivers are the natural sources of water for human consumption and information on these systems should therefore be obtained to monitor the health of these systems. The Modder River was selected as a case study because it is strongly impacted by anthropogenic disturbances such as impoundments, inter-basin transfer and indirect changes in the flow and sediments owing to land use changes. According to the present estimates by Seaman *et al.* (2001), the Modder River is exploited to full capacity.

1.3 METHODOLOGY

The investigation of sediment sources on thirty-six 5km segments of the Modder River was performed according to the procedures adopted from Kleynhans (1996). He videotaped the riparian zone and in-stream habitat integrity of the Luvuvhu River, on which he based a qualitative rating of the impacts of major disturbance factors such as water abstraction, flow regulation, and bed and channel modification. Kleynhans (1996:41) devised a system to assess the impact of these factors on relative frequency and variability of habitats on spatial and temporal scale gauged against habitat characteristics that could be expected to occur under conditions not anthropogenically influenced. In the present study, relative frequency and variability of characteristics of river channel morphology (bank erosion, gully erosion, tributary sediment input, riparian vegetation cover and dams/weirs) were investigated to determine the variability of significant sediment sources and stability on every 5km segment along the Modder River banks.

In addition, bank sediment samples were extracted from twenty-one sites along the Modder River for investigating the silt/clay content in the bank-forming material. The silt/clay content of the soil has long been recognised as influencing fluvial erosion and mass failures (Schumm, 1977:108; Knighton, 1987:71); the resistance of a bank to both processes tends to increase with increasing silt/clay content. The Global Positioning System (GPS) was used to pinpoint the position of every site in terms of latitude, longitude and height above sea level.

An objective-ranking scheme based on the frequency and variability of characteristics of river channel morphology permits the identification of the most unstable channel segments and, thereby, focuses attention on potentially "critical" segments (Simon and Downs, 1995:221).

Geographic Information Science (GIS) -based approaches (Finlayson and Montgomery, 2003:148) provided one of the few means available for systematically examining the spatial variability of sediment sources in the evolution of the Modder River landscape and to display observations in pictorial form (Coroza, Evans and Bishop, 1997:14). The application of these procedures will be fully explained in Chapter 4.

1.4 DETAILS OF PRELIMINARY STUDY

The Centre for Environmental Management (CEM) of the University of the Free State is responsible for the reports on the state of the Modder River and its ecological health. The CEM is commissioned by Bloem Water to carry out regular bio-monitoring of the Modder River, including its Habitat Integrity Assessment. Useful data were therefore available to realise the objectives of the study. There is also funding for fieldtrips of students making the Modder River their project within the framework of the CEM.

A pilot study (Tsokeli, 2003) was carried out on the Modder River in which the channel form was compared to a theoretical river model. In this research, the methods of Schumm (1977:134) and Chorley, Schumm and Sugden (1984:294) were applied. Firstly, the width : depth ratio was used as an index to describe the channel shape/form and secondly, the percentage of silt/clay in the bank-forming material was used as an index to the type of sediments being transported through the channel as well as an index of bank stability.

1.5 SIGNIFICANCE OF THE RESEARCH

The Department of Water Affairs and Forestry (DWAF) is the custodian of all water resources in South Africa, which makes it responsible for the care and management of water resources to ensure sustainable social and economic development. In 1994 DWAF launched the River Health Programme (RHP) to gather information on the health of South Africa's river systems (RHP, 2003:4). *The National Water Act* (NWA), Act 36 of 1998, recognises that it is best to manage aquatic ecosystems (including rivers) at catchment scale. This study can contribute to the central objective of South Africa's water policy, namely to plan and manage the efficient and sustainable use of water resources.

Knowledge of the spatial and temporal trends and dominant processes of channel adjustment in different environments is central to the maintenance and management of bridges, lands adjacent to stream channels, hazard mitigation and for public protection (Simon, 1995:611; Simon and Downs, 1995:216). The geomorphological perspective of this study can help managers define policies based on a longer-term perspective (Kondolf, Piégay and Landon, 2002:36). Improved understanding of catchment sediment sources is essential for designing and implementing management strategies to control off-site sediment-associated environmental problems (Collins and Walling, 2004:160).

1.6 RESEARCH OUTLINE

This chapter covers the purpose, necessity, focus, design, significance and details of the preliminary research for the study. The following chapter provides an overview of river research in geological literature. The focus is on bank erosion processes, sediment sources and transfer, and bank stability. Chapter 3 gives a detailed description of the

Modder River catchment area with the emphasis on the factors causing the delivery of sediments into the main course of the Modder River. Chapter 4 describes the methods used in the study. The main method is adapted from the qualitative procedures of Kleynhans (1996) for the assessment of the habitat integrity status of the Luvuvhu River (Limpopo system, South Africa). In addition, the methods devised by Simon and Downs (1995) were also applied. Chapter 5 presents the results of research on the channel morphology of the Modder River (bank erosion, gully erosion, bank material, tributary sediment input, riparian vegetation cover and dams/weirs). Chapter 6 interprets the data on channel morphology in the delivery of sediments, sediment transfer and bank stability, as well as pinpointing segments with a high potential for instability and flood risk.

CHAPTER 2
LITERATURE REVIEW

This chapter focuses on river research and the challenges and expectations in the management of the fluvial systems. The focus then shifts to the tasks, roles and progresses of Fluvial Geomorphology as a science studying fluvial systems. It then examines the differences between fluvial geomorphology and river management in past and current collaborations, as both disciplines are mutually dependent. The spatial variability, **sediment sources** (bank erosion and gully erosion), **sediment transfer** and **channel stability** within the river system are subsequently discussed with the main points of concern being the effects on bank erosion of riparian vegetation, bank material composition and dams and weirs along the river channel. Finally, the chapter focuses on what has been done on river research in South Africa.

2.1 RIVER RESEARCH

Rivers and river processes are considered some of the most important geomorphic systems on the earth's surface (Dardis, Beckedahl and Stone, 1988:30) and fluvial systems are among the most dynamic components of the landscape.

River research is strongly conditioned by the management requirements defined by environmental legislation (Mosley and Jowett, 1999:541). Principal areas of investigation at present include information on river morphology, habitat and in-stream flow required for the management of fluvial ecosystems, erosion, sediment transport and sediment yield, and gravel–bedded and braided river processes (Pizzuto, 1984: Brierley and Murn, 1997: Duan, 2001: Hooke, 2003: Collins and Walling, 2004 and Haschenburger and Rice, 2004). These investigations have evolved over time and relevant statutes have been introduced or repealed. Mosley and Jowett (1999:541) state that over the last 50 years, the emphases have shifted from the concern for general soil conservation and river control, to integrated catchment and river management, to a focus on recreational and in-stream uses, and finally to fully integrated resource management.

In order to manage a resource well, the nature, value and sensitivity of this resource must be clearly understood, making ongoing and thorough research essential. Mosley and Jowett (1999:542) state that the greatest challenges to river research relate to:

- “Requirements to safeguard the life-supporting capacity of air, water, soil and ecosystems”;
- “The need to recognise and provide for the preservation of the natural character of ... lakes and river margins”;
- “The need to have particular regard for the maintenance and enhancement of amenity values, the intrinsic values of an ecosystem and the protection of the habitat of trout and salmon”; and
- “The statutory requirement for local authorities to gather information on, and monitor the state of, the environment.”

However, knowledge alone does not suffice to manage rivers effectively; what is also essential is the appropriate attitude. According to Hooke (1999:374), for many decades the attitude toward physical management of rivers and hazards such as flooding and erosion was one of dominating and controlling nature without considering the dynamic character of the fluvial system. Hooke (1999:374) adds that the attitude was that all economic assets, including people, needed to be protected, and the population believed they had the right to this protection which often extended even to agricultural lands at a time when availability of land was thought to be at a premium and national policy was directed towards maximum agricultural production. Nevertheless, unforeseen events have a profound influence on environmental policy and are often the trigger for a change in attitude.

According to Macklin and Lewin (1997:15), the greatest challenge facing engineers, scientists and policy makers is river engineering and catchment management in developing sustainable solutions to river problems at a time of rapid, and in geological terms, unprecedented global environmental change. In times that bring about environmental uncertainty, engineers and catchment planners need to consider and solve problems of river instability within a global framework (Macklin and Lewin, 1997: 15).

One may be cynical about the reasons for the change in attitude, but the economics of river protection under global warming scenarios probably has as great a bearing as a ‘greening’ of attitude, itself a major breakthrough. It provides the basis for understanding river processes and landforms as being an integral and fundamental part of river engineering and management (Hooke, 1999:377).

2.2 FLUVIAL GEOMORPHOLOGY

Nowadays research on fluvial systems takes place within the ambit of fluvial geomorphology, a science that seeks to investigate the complexity of the behaviour of river channels at a range of scales from cross-sections to catchments (Dollar, 2002:123). It also seeks to investigate a range of processes and responses over a longer time-scale, usually within the most recent climatic cycle. According to Thorne (2002:201), “(P)rogress in the study of fluvial geomorphology rests on developing our capability to identify, investigate and understand the continuity and connectivity of flow processes and fluvial landforms in river systems. This prescribes the need to recognize and explore links that bind the fluvial system in space and time.”

For fluvial geomorphology to develop as a science, it must demonstrate its significance by contributing either to fundamental scientific issues that transcend boundaries, or to the solutions of pressing societal problems. Addressing this issue, Dollar (2000:385) points out that, as result of studies carried out by fluvial geomorphologists, it is now much easier to convince river managers of the need for geomorphological knowledge in managing fluvial systems scientifically and with due regard for human beings.

In recent years, therefore, fluvial geomorphology has made a considerable contribution to river management. An assumption of geomorphologists in managing fluvial systems is their understanding of the function of the fluvial systems at a range of spatial and temporal scales (Dollar, 2000:386). For instance, the ability to predict the response of a river to imposed change is based on geomorphologists’ understanding of the system. According to Sear and Newson (2003:18), “Monitoring change in the geomorphology of the river environment is therefore becoming an important measure both of river management practice and system resilience to external environmental change.” Knighton (1998:261) points out that it is also important to understand that not all fluvial systems respond to imposed change in the same way.

Macklin and Lewin (1997:16) contend that one of the main tasks of a geomorphologist is to identify those river basins or reaches that may be potentially susceptible to future environmental change and those presently subject to dynamic adjustment to altered channel or climatic conditions. Identification of the principal causative agents of past and present change and the differentiation between ‘natural’ and human impact on fluvial processes are fundamental prerequisites for alleviating present problems such as land degradation (Macklin and Lewin, 1997:16).

According to Newson, Hey, Bathurst, Brookes, Carling, Petts and Sear (1997:357), engineers, biologists and others are realising that fluvial geomorphology has a legitimate broad technical role, utilising numerical or statistical predictions, and having a qualitative observational and field measurement role that is much harder to codify and access. In some ways fluvial geomorphology is a practitioner’s work as a natural historian, basing some expertise on experience accumulated from observations in the field. Brierley, Fryirs, Outhet and Massey (2002:92) view fluvial geomorphology as an ideal starting point for evaluating the interaction of biophysical processes within a catchment, as geomorphological processes determine the structure or physical template of a river system.

To be more specific on the role of the geomorphologists, Thorne (2002:204) makes a strong case for project-related, site-specific, applied geomorphic studies to encompass a wide range of spatial and temporal scales. River engineers, policy makers and managers today recognise the importance of accounting for channel morphology and the dynamics of fluvial systems when dealing with alluvium rivers. Thorne (2002:204) argues that, “Modern approaches to river management require engineers to work *with* rather than work *against* the natural process-form relationships of a river, by retaining as much as possible of the natural hydraulic geometry of the self-formed channel when performing works for river regulations, channel training, navigation, flood defence and land drainage.”

An understanding of geomorphic processes and the determination of appropriate river structure and function at differing positions in catchments are critical components in sustainable rehabilitation of aquatic ecosystems. Brierley *et al*. (2002:92) stipulate that these interactions induce direct controls on the distribution of flow energy dictating local-scale patterns of erosion and deposition at differing flow stages.

In the fluvial field, catchment management plans are being produced, again incorporating a very large number of facets of activity in river basins. In these, the geomorphological element is less explicit and can be quite minor in the final product, but Brookes (1995:608) stresses the application of fluvial geomorphology and the key role of classifying reaches. At a smaller scale, in many important reaches of rivers where problems are arising or developments are proposed, the technique of fluvial auditing is being applied. This method is a detailed geomorphological mapping of a reach in which the processes and landforms are identified.

River channel maintenance is a multi-million pound (Sterling) management function. For instance, in England and Wales engineering direction with geomorphological insights is proving increasingly valuable, especially for sensitive sites or sites where costs could be cut by controlling sedimentation or erosion (Newson *et al*., 1997: 332).

2.3 GEOMORPHOLOGY AND RIVER ENGINEERING

Two scientific traditions have evolved around the study of river channels in Great Britain and America, namely fluvial geomorphology and river engineering (James, 1999:265). Although differences between these disciplines may become blurred by collaborations and an exchange of ideas, a persistent contract between geomorphologists and river engineers should be understood to facilitate communication and appreciate various approaches to river management. James (1999:266) believes that the comparisons between fluvial geomorphology and river engineering reveal both as valuable disciplines. Each has much to learn from the other, but a fundamental difference exists in the perception of time and therefore of fluvial processes.

According to Sear, Newson and Brookes (1995:629), the connectedness of fluvial geomorphology and river engineering shows that they are converging disciplines and can mutually benefit each other. This convergence is brought about by the increasing demands on river managers to enhance the water environment and to develop sustainable strategies. Engineering practice has enjoyed the patronage of politicians and the affluent business aristocracy (permitting the development of respected institutions) while fluvial geomorphology has evolved in the academic environment (Sear *et al*., 1995:629). Table 2.1 compares the respective approaches of fluvial geomorphology and river engineering.

Table 2.1: Comparisons of river engineering and geomorphological approaches

Engineering	Geomorphology
- Traditional	- Untried
- Quantitative	- Qualitative
- Problem oriented	- Academic
- Reach-based	- Catchment-based
- Office-based	- Field-based
- Auditable	- Flexible

Source: Sear *et al*., 1995:630

Although scientific collaborations between engineers and geomorphologists studying river systems have increased rapidly in recent decades, many basic differences remain.

River engineering evolved predominantly from studies of fluid mechanics, hydraulics and regime theory (James, 1999:267). Owing to an emphasis on factors relevant to channel hydraulics and structural competence, engineering studies have traditionally focused on channel gradients, channel and floodplain topography, including bed-forms, roughness elements and the geotechnical properties of materials. Engineers have developed a range of structural procedures to stabilise and train sections of channel to prevent bed scour or shoaling, bank erosion and channel migration (Hey, 1997: 5). Because engineers often work in a pragmatic environment with government institutions, consultants and contractors, there has been an emphasis on practical solutions and symptoms rather than on underlying processes (Sear *et al*., 1995:629), thus focusing on relatively short time-periods.

On the other hand, geomorphology has evolved largely in research-oriented environments, e.g., universities, professional associations and geological surveys, from physiographic studies that can be divided into genetic or historical methods and descriptive methods. At the turn of the century the genetic approach by Davis (1902) dominated and geomorphic research largely dealt with landform evolution over millions of years, seemingly inappropriate in the realm of the engineer (Gilvear, 1999:230; James, 1999:267). The descriptive approach based on equilibrium theory gradually developed from the work of Gilbert (1877), introducing concepts such as grade, dynamic equilibrium and landform entropy, with a greater emphasis on prediction through the identification of process-response linkages (James, 1999:267).

It is now possible for geomorphologists to review the potential contribution of their techniques to both engineering design and maintenance problems from a position of practical experience. Fluvial geomorphology has made great contributions to river maintenance practice through developing a broad classification of river channels based on their morphology and sediments. Such a classification offers a comparative standard for the evaluation of problems and remedial options (Sear *et al*., 1995:633). Similarly, qualitative guidance on the active processes and cause/effect relationships at the reach and catchment scales allows better targeting of the most appropriate conventional solutions or innovative remedies and the prediction of their impacts. A major contribution of geomorphology is to the prediction of sediment transport rates and morphological parameters, such as channel dimensions and morphological features, both natural and structural.

Gilvear (1999:230) states that “The change in the relationship between fluvial geomorphology and engineering has resulted in part from a trend towards process studies, increased professionalism among geomorphologists, greater quantification, adoption of common methodologies and tools (i.e., computer-based hydraulic modelling, remote sensing, GIS, GPS, etc.).” In addition, the recent interest in geomorphology stems from the desire to minimise flood damage, the requirement to reduce environmental degradation as a result of river engineering schemes, a move towards restoring sterile canalised river channel reaches to ecologically valuable and aesthetically pleasing watercourses and concern with regard to the response of river channels to climate change scenarios (Gilvear, 1999:230).

The issues above, together with geomorphological river restoration, present an enormous challenge to engineers. Geomorphological approaches and input will need to be the major component of tackling such challenges.

2.4 SPATIAL VARIABILITY

Channel variability is a characteristic feature of natural streams and is significant in several contexts, including channel morphology, stream hydraulics, water quality and physical habitat (Western, Finlayson, McMahon and O'Neill, 1997: 50). There is an increasing recognition that the interaction between vegetation, sediment and geomorphology is important for understanding process-form relationships in a fluvial system (Dollar, 2002:129). Variations in the shape and size of alluvial channel cross-sections result from several interacting features of the system, including the discharge characteristics, the quantity and characteristics of the sediment load and the perimeter (bed and bank) sediments that form the channel boundaries (Western *et al*., 1997: 50; Goodson, Gurnell, Angold and Morrissey, 2002:45). The natural variability in bank erosion reflects variations in the resistance of the banks to erosion and the forces the river exerts on the banks (Goodson *et al*., 2002:45).

Variations in the materials forming the bed and banks, the vegetation cover and the hydrological processes within the banks determine the resistance of the banks to erosion. Over time, the interaction between force and resistance is moderated by the river's transport of both mineral and organic sediment. These have the potential to aggrade river banks and, by enhancing the growth and establishment of vegetation, to increase bank strength as root systems and above-ground vegetation biomass are developed (Goodson *et al*., 2002:45).

According to Rinadli and Casagli (1999:254), "The differences in bank geometry and geotechnical properties along a river introduce a reach-and-basin scale spatial variability in bank stability, while temporal variations in bank stability at individual sites are associated with change in pore pressure induced by rainfall and flow events, as well as by seasonal vegetation growth and the alternation of desiccation and freeze–thaw processes.”

On the other hand, at the catchment-scale there is a tendency for width, depth and therefore cross-sectional area increases downstream, with the width increasing more rapidly than depth. These trends are associated with a downstream increase in discharge (Western *et al*., 1997: 39). Given relatively uniform supply conditions and a tendency for transported sediment to become finer downstream, channel banks should become more cohesive downstream and have a higher silt/clay content which is a measure of their erosive resistance (Knighton, 1998:175).

Channel responses often include progressive upstream degradation, downstream aggradation, channel widening or narrowing, channel shifting and changes in the quantity and character of the sediment load and surface texture (Simon, 1995:612; Simon and Downs, 1995:215; Kondolf *et al.*, 2002:36).

2.5 SEDIMENT SOURCES

Sediment sources are spatially and temporally variable in response to the complex interactions between the major factors governing sediment mobilisation and delivery (Collins and Walling, 2004:161). Different types of sediment sources can be classified in terms of hill slopes and river channels (bed and banks), or the surface and subsurface characteristics of a catchment, while spatial sources can readily be categorised according to individual tributary sub-catchments or geological units. Alternatively, research has also demonstrated that in some cases channel bank erosion can be an important, if not a dominant, source of sediment loads (Collins and Walling, 2004:160).

In the analysis of factors that influence sediment sources, Table 2.2 documents some potential destabilising phenomena at catchment and reach scales that can be used in fluvial auditing or in the interpretation of sediment related problems, together with the identification of indicators of channel instability and stability within a sediment system given in Table 2.3.

Table 2.2: Potential sediment sources at catchment and reach scales

Increased sediment supply	Decreased sediment supply
Catchment scale - Climate change (> rainfall) - Upland drainage - Afforestation - Mining spoil inputs - Urban development - Agricultural drainage - Soil erosion	- Climate change (< rainfall) - Dams/regulations - Cessation - Vegetation of slopes/scars - Sediment management
Reach scale - Upstream erosion - Agricultural runoff - Tributary input - Bank collapse - Tidal input - Straightening - Upstream embanking	- Upstream deposition - Sediment trapping - Bank protection of erosion - Vegetation of banks - Dredging (shoals/berms) - Channel widening - Upstream weirs

Sources: Sear *et al*., 1995:368; Newson *et al*., 1997:358

2.5.1 Bank erosion

One of the main processes affecting channel change is bank erosion (Dollar, 2002:131). River bank erosion can present serious problems to river engineers, environmental managers and farmers through loss of agricultural land, delivery of large volumes of sediment with associated sedimentation hazards in the downstream reaches of the fluvial system, damage to ecological habitats and riparian vegetation, and occasional riverine boundary disputes (Lawler, Thorne and Hooke, 1997:137; Rinaldi and Casagli, 1999:253 and Dapporto, Rinaldi and Casagli, 2001:222).

Table 2.3: Indicators of channel stability and instability

	Upland	Transfer	Lowland
Evidence of incision/erosion	- Perched boulder berms - Terraces - Old channels - Old slope failures - Undermined structures - Exposed tree roots - Narrow/deep channels - Bank failures, both banks - Armoured/compacted bed - Deep gravel exposure in banks topped with fines	- Terraces - Old channels - Narrow/deep channels - Undermined structures - Exposed tree roots - Bank failures, both banks - Armoured/compacted bed - Deep gravel exposure in banks topped with fines	- Old channels - Undermined structures - Exposed tree roots - Narrow/deep channels - Deep gravel exposure in banks topped with fines
Evidence of aggradation	- Buried structures - Buried soils - Large, uncompacted bars - Eroding banks at shallows - Contracting bridge space - Deep fines sediment over course gravels in bank - Many unvegetated bars	- Buried structures - Buried soils - Eroding banks at shallows - Large uncompacted bars - Contracting bridge space - Deep fines sediment over course gravels in bank - Many unvegetated bars	- Buried structures - Buried soils - Large silt/clay banks - Eroding banks at shallows - Contracting bridge space - Deep fines sediment over course gravels in bank - Many unvegetated bars
Evidence of stability	- Vegetated bars and banks - Compacted weed-covered bed - Bank erosion rare - Old structures in position	- Vegetated bars and banks - Compacted weed-covered bed - Bank erosion rare - Old structures in position	- Vegetated bars and banks - Weed-covered bed - Bank erosion rare - Old structures in position

Sources: Sear *et al*., 1995:638; Newson *et al*., 1997:358

According to Hughes and Prosser (2003:12), riverbank erosion is the most uncertain of the sediment source terms in the river budget modelling. It is known that degradation of riparian vegetation and other impacts on rivers have resulted in greatly increased rates of riverbank erosion, to the extent that this erosion process cannot be ignored as a sediment source in regional assessments (Hughes and Prosser, 2003:12). In some landscapes, bank erosion may be an important, if not the dominant process in terms of its contribution to river sediment supply.

Many studies of bank erosion have tended to focus either at the site specific scale, emphasising the relationship between erosion processes and engineering properties of bank materials (e.g. Thorne and Tovey, 1981:469; Brierley and Murn, 1997:120), or the planform scale, relating rate of concave bank retreat to channel geometry and the pattern of bend development. It is generally recognised that bank erosion usually reflects a combination of processes and that, in view of downstream changes in bank material character (i.e. erodability) and flow hydraulic relations (i.e. erosivity), differing process domains can be distinguished.

Brierley and Murn (1997:120) point out that there are remarkably few studies that have examined and explained the broader, catchment scale distribution of bank erosion. This is somewhat surprising, as longer-term controls on sediment transfer may play a critical role in determining the within-catchment distribution, rate and character of bank erosion. Conceptual models of bank retreat and the delivery of bank sediments to flow emphasise the importance of interactions between hydraulic forces acting at the bed and bank toe, and gravitational forces acting at the bank (Simon, Curini, Darby and Langendoen, 2000:194). The combination and interaction of gravitational forces acting on the bank material, and the hydraulic forces acting on the bank toe and channel bed, determine the rate and style of bank erosion (Dollar, 2002:131).

Stott (1997:383) declares, “Factors controlling stream bank erosion have attracted attention from geomorphologists, hydrologists and river engineers for several decades.” Bank erosion consists of the detachment of grains or assemblages of grains from the bank surface, followed by fluvial entrainment (Lawler *et al*., 1997:150). It generally occurs through three primary mechanisms, namely bank failure, fluvial entrainment and sub-aerial weakening and weathering (Abemethy and Rutherfurd, 1998:56; Duan, 2001:702; Dollar, 2002:131; Hughes and Prosser, 2003:14).

Fluvial entrainment refers to the removal of individual grains or aggregates by the shearing action of flow (Lawler *et al*., 1997:152). Bank failure refers to the slumping or collapse of sections of the riverbank when critical height for stability has been exceeded. It is commonly caused by mechanical instability of the bank material which is related to the cohesiveness, repose angle, vegetation coverage, pore pressure, length of tension crack and rate of basal/undercut erosion (Duan, 2001:702). Flow-induced shear stress acting on the submerged part of the bank surface causes basal erosion. A number of complementary processes, including soil piping and sapping, may also occur. Frost heave and desiccation cracking may also influence subsequent fluvial erosion (Miller and Quick, 1998:1005).

The fundamental mechanism of bank failure is basal erosion destabilising the upper part of the bank. In case of a meandering channel, the basal erosion occurs at the downstream end of the concave bank, while the convex bank advances (Lawler *et al*., 1997:148). Thus, bank failure frequently occurs at the downstream end of the concave bank, and the convex bank is relatively stable. Bank erosion eventually causes bank advance or retreat. Advance is caused by sediment deposition near the bank. The deposited sediment may be supplied from eroded bank or bed material transported from upstream (Lawler *et al*., 1997:148). In natural rivers, lateral erosion and bed degradation tend to increase the slope of the bank, characteristically forming an almost vertical cut. Bank failure due to geotechnical instability may dominate the bank erosion process, for example, in incised channels.

Simon *et al*. (2000:197) observe that processes occurring at the bank toe are central to the understanding of bank failure and the evolution of bank failure through time. During degradation phases of channel evolution, bank heights are greater and the bank surfaces below riparian tree roots become exposed. Consequently, *in situ* bank toe material is more susceptible to basal erosion than in a non-incised channel (Simon *et al*., 2000:197). According to Thorne and Abt (1993:835), “Serious riverbank erosion retreat usually occurs through the combination of fluvial erosion of intact bank material and bank failure under gravity.” The highest rates of bank retreat are known to occur because of high flows during prolonged wet periods, rather than simply the largest storms or floods (Simon *et al*., 2000:193; Dollar, 2002:131; Couper, 2003:96). Failure takes place when erosion of the bank and channel bed adjacent to the bank has increased the height and steepness of the bank to the point that it reaches a condition of limiting stability (Richards and Lane, 1997:278; Abam and Omuso, 2000:111). The mechanics of failure depend on the engineering properties of the bank material and the geometry of the bank at the point of collapse.

Eroding banks are usually steep and often fail by a slap-type mechanism where a block of soil falls forward into the channel. Determining the nature of tension cracks between the block and the bank are important in controlling the geometry of failure block and the timing of failure. Following the failure, slump debris comes to rest around the bank toe that is on the lower bank and the river next to the toe.

While in place, this debris acts to increase bank stability by loading the toe, buttressing the bank and protecting the intact bank material below from direct attack and entrainment by the flow (Thorne and Abt, 1993:835; Duan, 2001:702). However, the slump debris is more or less disturbed and disaggregated in the failure and so it is much less resistant to erosion by the flow than the intact bank. Hence, the residence time of slump debris at the toe is often quite short, because flow in the channel is able to quickly entrain and remove it. This is especially so if the forces of fluvial erosion are concentrated on the bank and on the bed adjacent to the toe, as is the case at the outer bank in meander bends and in unstable channels subject to degradation and rapid widening.

After removing the slump debris in the basal clean-out phase of the erosion cycle, the flow once more attacks the intact bank and bed material, again reducing bank stability to the critical level and leading to further mass failure (Thorne and Abt, 1993:836; Abam and Omuso, 2000: 115). If, in the long term, the flow is able to complete basal clean-out and re-erode the banks sufficiently, it triggers further failures.

The bank retreat rate is determined by the capacity of the flow to erode and remove sediment (intact and slump debris) from the toe area. Bank retreat, however, may occur by slumping, toppling, sliding or simply by the erosion of individual soil peds. Each of these mechanisms is controlled by a different soil property; slumping, for example, is controlled by the shear strength of the soil, while toppling is controlled by tensile strength (Pizzuto, 1984:113; Abam and Omuso, 2000:115). The investigation of sub-aerial processes occurring in the field has to date been limited. Abemethey and Rutherfurd (1998:62) suggest that this may be due to the seasonal nature of such processes and to the difficulty associated with separating them from fluvial erosion and mass failure.

Bank retreat research tends to focus on fluvial erosion and mass failure, while sub-aerial activity is often considered simply as a `preparatory' process that weakens the bank face prior to fluvial erosion, thus increasing the impact of the latter. The interrelationships between sub-aerial and other processes of erosion, and the consequent implications for bank morphology, have not yet been sufficiently explored (Couper, 2003:95).

2.5.1.1 Effects of cohesive bank material on bank erosion

The principal erosion mechanisms that operate on cohesive riverbanks can be considered in terms of two distinct processes: mass failure and fluvial entrainment (Miller and Quick, 1998:1005). According to Rinaldi and Casagli (1999:258), fluvial processes are less effective in eroding the silty sand material of the upper bank than the basal gravel, owing to its high resistance to erosion. The cohesive soil of the upper bank is quite resistant to erosion by the fluvial entrainment of individual particles at the bank surface. According to Thorne and Tovey (1981:471) and Rinadli and Casagli (1999:58), field observations show that unless the surface of a cohesive bank is loosened or weakened by processes such as frost heave or thorough wetting, fluvial entrainment alone is not particularly instrumental in causing erosion. Also, the position of the cohesive layer at the top of the bank results in a much lower frequency of attack by the flow.

In analysing the stability of cohesive banks, it is important to take into account the weakening effect of tension cracks. They reduce the effect of the potential failure surface and decrease bank stability, but they do not invalidate the stability analysis, provided the depth of the tension cracking is small compared to the bank height (Thorne and Tovey, 1981:473).

2.5.1.2 Effects of non-cohesive bank material on bank erosion

According to Nagata, Hosoda and Muramoto (2000:245) and Duan (2001:702), bank erosion with non-cohesive material involves four processes:

- bed or bank erosion owing to hydraulic force;
- bank collapse owing to geo-technical instability;
- deposition of collapsed bank material at the front or toe of the bank; and
- transportation of the deposited material.

The bank collapses when the down-slope component of the gravitational force exceeds the frictional force acting on the failure surface. The material from bank failure may be carried away by flow or deposited at the toe of the bank.

Non-cohesive materials are relatively coarse-grained and are usually well drained; pore water pressure is consequently seldom a significant factor. Thorne and Tovey (1981:471) comment, “Observations of erosion of cohesionless banks make it clear that particles in the sand and gravel size range are highly susceptible to erosion by fluvial entrainment. Fluvial erosion of the lower part of a non-cohesive bank can cause over-steepening and slip failures higher up the bank. Non-cohesive banks fail by the dislodgement of individual clasts or by shear failure along shallow, very slightly curved slip surfaces.”

The stability of a non-cohesive bank depends only on the angles of the slope and the internal friction; that is, if there is no pore pressure or external forces. Failure may be brought about by increasing the slope angle (over-steepening), or by reducing the friction angle (Thorne and Tovey, 1981:471).

2. 5.1.3 Effects of vegetation on bank erosion

Vegetation impacts are complex and their overall impact may be beneficial, neutral or detrimental to bank erodability and stability (Lawler *et al.*, 1997:162).

2.5.1.3.1 Prevention

Riparian vegetation is an important component of bank strength. Well-vegetated banks are some 20 000 times more resistant to erosion than similar bank sediment without vegetation (Stott, 1997:395; Abemethy and Rutherfurd, 1998:56; Simpson and Smith, 2001:339). The main role of vegetation in stabilising banks against mass failure is increased bank-substrate strength due to the presence of roots. Vegetated banks in flood-plain reaches can maintain higher and steeper geometries than their vegetation-degraded counterparts (Abemethy and Rutherfurd, 2000:921).

Forest vegetation is an efficient means of combating erosion as it protects soils against erosive agents, regulates hydrological regimes and improves the physical and chemical properties of the soil. Consequently, vegetation is important for soil protection. According to Rey (2003:550), studies have shown that erosion generally decreases with increased vegetation cover. Vegetation protects banks by creating a lower velocity buffer between the soil and the eroding forces of the main current. Dense roots can reinforce and protect banks in a rip-rap fashion. Furthermore, plant cover reduces frost susceptibility, thereby increasing bank stability (Zonge, Swanson and Myers, 1996:47).

Some researchers question whether woody vegetation is more resistant to erosion than grass and root materials. Studies conducted by Simpson and Smith (2001:339) along Coon Creek in Montana USA; show that grass-covered banks are narrower than nearby forested reaches. In addition, studies by Rey (2003:560) show that vegetation distribution in gullies is important for reducing sediment yield at their outlets; low vegetation in the gully floor traps sediments and thus plays an especially significant role. Natural rates of bank erosion may be very low with intact riparian vegetation and that erosion is greatly accelerated with removal of riparian vegetation (Abemethy and Rutherfurd, 2000:921; Hughes and Prosser, 2003:12). Trees can reduce erosion through their roots' mechanically strengthening and binding the banks.

2.5.1.3.2 Increase

A channel bank planted with trees may have a different moisture regime to banks with adjacent farmland. Since trees intercept rainfall, utilise soil moisture to replace that lost by transpiration, and shade the soil surface during sunny weather, stream banks under trees are likely to undergo fewer wetting and drying cycles, which may be important in loosening material and 'preparing' banks for future erosion (Stott, 1997:396). Trees may also shade and suppress shorter riparian vegetation that helps to bind bank materials, leading to increases in channel widths. Roots are often cited as providing lines of weakness in a bank, particularly in dying or dead plants. It is a commonly held view that the surcharge of trees on a riverbank may result in bank instability (Lawler *et al*., 1997:155; Stott, 1997:396).

Large woody debris generally form at channel constrictions, such as under bridges or in shallow channel sections where flow is divergent; it may cause localised flooding and erosion where flow is deflected towards channel banks (Downs and Simon, 2001:66), resulting in an increase in lateral bank erosion and causing channel widening (Haschenburger and Rice, 2004:243). During tree-fall, large amounts of sediments are transferred to the flow, but where the trees remain upright, the banks often undercut below the 0,3 – 0,5m root zone (Abemethy and Rutherfurd, 1998:57).

2.5.2 Gully erosion

Recent studies indicate that gully erosion represents an important sediment source in a range of environments; that gullies are effective links for transferring runoff and sediment from uplands to valley bottoms and permanent channels where they aggravate the off-site effects of water erosion (Poesen, Nachtergaele, Verstraeten and Valentin, 2003:96). In other words, once gullies develop, they increase the connectivity in the landscape. Many cases of damage (sediment and chemical) to watercourses and properties by runoff from agricultural land relate to (ephemeral) gullying. Consequently, there is a need for monitoring, experimental and modelling studies of gully erosion as a basis for predicting the effects of environmental change (climatic and land use changes) on gully erosion rates.

Gully erosion is defined as the erosion process whereby runoff water accumulates and often occurs in narrow channels and, over short periods, removes the soil from this narrow area to considerable depths (Poesen *et al*., 2003:92). For agricultural land, permanent gullies are often defined in terms of channels too deep to improve readily with ordinary farm tillage equipment, typically ranging from 0,5m to as much as 25 - 30m in depth.

Bank gullies are formed where concentrated flow crosses an earth bank, e.g. a terrace or a river bank (Vandekerckhove, Poesen, Wijdenes and Gyssels, 2001:134; Poesen *et al*., 2003:95). Once initiated, bank gullies retreat by head-cut migration into the more gentle sloping soil surface of the bank shoulder and further into low-angled pediments, river or agricultural terraces (Poesen *et al*., 2003:95). Such bank gullies contribute to land degradation and sediment production, leading to severe management problems related to land-use and hydrologics. Climate and land-use changes are crucial factors in the development initiation and retreat of these erosion features (Vandekerckhove *et al*., 2001:134).

In the study by Watson (1990: 73) it was found that most of the sediment transported by gullies is detached by head retreat and channel wall failure. Two processes are involved in head retreat. Firstly, through flow from the scarp detaches particles. Secondly, the scouring action of flowing water undercuts the base of the banks leading to their collapse.

The failure of the banks also involves two processes. Firstly, saturation during flow may lead to slumping. Secondly, the scouring action of flowing water undercuts the base of the banks leading to collapse.

2.6 SEDIMENT TRANSFER

It is generally assumed that a channel functions as a system and that sediment is moved through the system (Hooke, 2003:80). Sediment load consists of suspended and material loads, while suspended load transport is dependent on the turbulence and velocity of flowing water; bed-load material is moved by shear along the bottom of the stream (Chorley *et al*., 1984:293; Camenen and Larson, 2005:249). The most efficient channel for transporting suspended load is one that is relatively narrow and deep, whereas the most efficient channel for moving bed-load with the same quantity of water will be wide and shallow, implying a large width : depth ratio, but a channel transporting a small quantity of the bed material load will have a relatively low width : depth ratio (Chorley *et al*., 1984:294; Knighton, 1998:175).

2.6.1 Effects of impoundments (dams and weirs)

The geomorphological impacts of impoundments have been described by a number of authors (e.g. Rowntree and Wadeson, 1998:133; Verstraeten and Poesen, 2000:220; Hooke, 2003:85). Dams have two immediate effects: the first is to trap sediment behind the dam wall and therefore reduce the sediment supply to the channel within the lifetime of the structure. Secondly, by storing water, dams reduce both the magnitude and frequency of floods.

Impoundments, regardless of their size or function, capture stream flow from rivers of different magnitude (Verstraeten and Poesen, 2000:220). Together with the streamflow, suspended and bed-load sediment will enter the reservoir or pond and part of it will be deposited. Verstraeten and Poesen (2000:220) maintain "It is the nature of rivers that they transport sediment, and it is of the nature of reservoirs that they should reduce the velocity of flow from that of the natural river and so encourage sediment deposition." Sedimentation within reservoirs or ponds is a problem, as it decreases the storage capacity of the dam and, hence, makes it less efficient (Verstraeten and Poesen, 2000:220). Especially in small ponds, sedimentation can become a severe problem, as their rate of siltation is generally much higher than that of large dams. The useful life of these ponds is therefore very limited unless they are dredged frequently.

Possible impacts may be summarised as follows (Rowntree and Wadeson, 1998:133):

- Degradation and armouring immediately below the dam owing to the removals of fines by sediment-free water.
- Accommodation adjustment, wherein the resistant nature of the channel and lack of sediment inputs prevent significant changes to the channel.
- An unconnected system with localised responses budgets (Hooke, 2003:93), owing to the reduced flow in the main channel being incompetent to transport continued sediment inputs from tributaries and coarse sediments.

These effects may lead to narrowing or deepening of the channel and contraction as the channel becomes adjusted to the reduced flood flows.

2.6.2 Effects of vegetation

Vegetation in the channel bed impedes erosion and the movement of coarse sediments owing to a lack of competence and resulting in an unconnected system (Hooke, 2003:93). Woody debris acts as a hydraulic roughness element that reduces the momentum of the flow and the capacity of the channel to transport sediment

(Haschenburger and Rice, 2004:242). Depending on their permeability and the degree to which they span the channel, they may pond, deflect or otherwise retard the streamwise passage of water. The associated reduction in bed shear stress then leads to localised sediment deposition. Jams may act as a barrier to sediment transport, whereby particles in motion are physically prevented from downstream movement (Haschenburger and Rice, 2004:242).

2.7 STREAM-BANK STABILITY

Channel morphology and stability could be expected to reflect the net sediment budget with evidence of erosion, net aggradation or approximate balance (Hooke, 2003:80). The alluvial channel changes naturally with time, because it is formed in readable sediments and because the stress exerted by the flowing water often exceeds the strength of the sediment forming the bed and banks of the channel (Chorley *et al*., 1984:302). Theories explaining channel change are as diverse as the channel patterns themselves, but certain recurring themes may be identified. Winterbottom (2000:196) defines river channel change as a variation in form that constitutes a departure from a state of dynamic equilibrium. The dynamic equilibrium in a river channel is a state whereby a channel is adjusted to its discharge regime and, although the processes of erosion and deposition still continue, the overall form is preserved to produce a dynamically stable pattern.

Stream-bank stability has long been a concern for land managers, but the processes involved are incompletely understood (Zonge *et al*., 1996:47). During droughts, low stream flows may allow bank sediments to accumulate at slope toes. Consequently, vegetation may become established on the new substrate. Once lower banks are stabilised by vegetation, and if the incised channel is wide enough to be near a dynamic equilibrium, stream bank erosion along the active channel may decrease (Zonge *et al*., 1996:47).

The stability of the river bank depends on the balance of forces, motive and resistance, associated with the most critical mechanism of failure (Thorne and Tovey, 1981:469), as well as other factors, such as bank material composition and strength, local channel form and organic debris dams, the stream hydrological regime, the role of ground water and antecedent soil moisture, the incidence of frost heave and formation of ice needles. The species of trees (conifers or deciduous) and the type of under-story vegetation, can all influence bank erosion rates (Stott, 1997:396).

A stable bank can be transformed into an unstable bank during periods of prolonged rainfall through increases in specific weight, a decrease in metric suction, generation of positive pore-water pressures, entrainment of *in situ* failed material and loss of confining pressure during a receding limb of the hydrograph (Simon *et al*, 2000:215). Simon *et al*. (2000:215) and Dollar (2002:131) argue that it is not necessarily the large, infrequent floods that induce bank failures, but rather prolonged periods of rainfall that weaken bank materials - resulting in mass failure.

Braiding rivers are wider than meandering rivers, relative to discharge. This suggests that bank strength, which is influenced by silt/clay content and vegetation, exerts a strong influence on river morphology and, if removed or altered, can change the channel pattern (Simpson and Smith, 2001:339). Erosion of channel banks is important for two reasons: it is a dominant process in terms of its contribution to river sediment load (Stott, 1997:383) and widening decreases flow stability, thus increasing bar formation.

Channel stability is of great concern in the design of major irrigation systems and for water engineering. It is necessary for the channel to be stable (Chorley *et al*., 1984:292). The regime channel could aggrade or degrade slightly. The ideal situation is for a channel at a given time to be in similar shape, dimensions and positions to the previous rainy season. Some simple quantitative relationships that relate velocity of flow, channel depth and discharge to the channel dimensions were developed by engineers to facilitate the design of stable channels.

2.7.1 Effects of bank materials on channel stability

Many authors have attempted to define the relationship between bank erodability and the cross-sectional geometry of rivers (e.g. Schumm, 1977:108; Abam and Omuso, 2000:111). Bank material characteristics are an important sedimentological control on the strength and stability of channel banks and therefore on the adjustment of the channel width (Knighton, 1987:175). Soil particle size and, particularly, the silt/clay content of the soil have long been recognised as influencing fluvial erosion and mass failures; the resistance of a bank to both processes tends to increase with increasing silt/clay content (Schumm, 1977:108; Knighton, 1987:71).

The resistance to bank erosion is usually represented by a textual property of the soil such as the percentage of silt/clay (Schumm, 1977:134; Chorley *et al*., 1984:293). The percentage of silt/clay in the perimeter of a channel reflects the nature of sediment moving through that channel. The type of sediment load is considered to be a more important control on stable channel shapes than the total quantity of sediment transported through the channel (Schumm, 1977:110). A channel with a small quantity of bed load may exert the dominant control on the channel if it is the total load, whereas in another channel the same amount of bed load may exert much less influence on channel shape because it is only a small part of the total sediment load. Schumm (1977:110) hence concludes that when suspended-sediment load and discharge are constant, an increase in the quantity of bed-load causes an increase in channel width and the width : depth ratio, but this is also related to increased gradient and velocity of flow associated with the increase of bed-load.

Rivers with weak, easily eroded banks are usually found to be wide and shallow, while rivers with resistant banks are usually found to be narrow and deep (Abam and Omuso, 2000:111). Silt/clay particles are much more difficult to erode because of the grain-to-grain cohesion that is largely absent in sand. This reduction in bank strength in the braiding reach is a critical factor affecting channel morphology (Simpson and Smith, 2001:347). River widening requires an easily redoubled channel perimeter. A high silt/clay percentage in the meandering reach increases bank strength and prevents widespread lateral erosion. Channel widening in the braiding reach is critical, because it influences the effectiveness of the available stream power.

Pizzuto (1984:113) argues that a single parameter cannot adequately represent the resistance of all banks to retreat by all erosional processes and failure mechanisms, particularly when the parameter is a textual property rather than a direct measure of soil strength. A more meaningful approach is to identify the dominant erosional process which controls the erosion and retreat of a particular type of riverbank. Once the dominant erosional process is clearly defined, a soil property may be chosen to represent the resistance of specific riverbanks to retreat by the particular mechanism. Bank resistance and the management of channel width are strongly related to the strength of the less cohesive basal layer, erosion of which induces block failure in the undercut cohesive material.

Rivers flowing through alluvial deposits often have composite banks composed of non–cohesive and cohesive material (sandy silt/clays deposited by over bank flow, in abandoned channels and emergent bars) (Thorne and Tovey, 1981:469).

2.7.2 Effects of vegetation on channel stability

There has been an increasing interest in the role of vegetation in fluvial geomorphology in recent years because it has been recognised that river dynamics cannot be fully understood without taking into account the impact that vegetation, both on the banks and within the channel, has on bank stability (Wallerstein and Thorne, 2004: 53).

According to Lawler *et al*. (1997:154), the results of recent research indicate that the potential impact of bank vegetation on the overall flow capacity of the channel is strongly related to the width : depth ratio; vegetation resistance on the banks is only significant in channels with width : depth ratios of less than about 12. The effects of vegetation are probably greatest on small rivers (Lawler *et al*., 1997:154; Eaton and Miller, 2004: 41). Vegetation can either increase or decrease bank stability, depending on the type of vegetation, bank geometry and bank material. Stott (1997:396) cites that there are conflicting reports in literature regarding the effects of vegetation on channel bank stability.

Large woody debris (LWD) resulting from tree-fall into rivers is a natural phenomenon in wooded river systems. LWD can affect the hydrology and hydraulics of flows, the transport and storage of sediments, solutes and other organic matter, and the spacing and variance of fluvial geomorphology features (Downs and Simon, 2001:66). River managers involved in flood defence often regard accumulated LWD as an obstruction to the passage of flood flows and have tended to remove trees from banks for fear of their increasing channel roughness during times of flood, as well as the possibility of their being added to the debris carried by a flooding river, jamming in bridges, weirs and other such structures downstream. Fallen trees (or large woody debris) can span and partially block the channel, often causing flow in two or more sub-channels (Downs and Simon, 2001:66; Stott, 1997:396; Abemethy and Rutherfurd, 1998:59).

The study by Friedman, Osterkamp and Lewis (1996:342), *The role of vegetation and bed-level fluctuations in the process of channel narrowing*, has also shown that vegetation contributes to channel narrowing by increasing deposition and bank instability.

2.8 SOUTH AFRICAN STUDIES ON RIVERS

South African river systems are strongly impacted by anthropogenic disturbances such as impoundments, inter-basin transfer, indirect changes in the flow and sediments due to changes in land use (Rowntree and Wadeson, 1998:125). Many fluvial systems in South Africa are either semi-controlled, controlled by bedrock or are fundamentally different from alluvial systems. An example is that of rivers in the Kruger National Park, showing that the bedrock has a major impact on the rates and processes of sediment erosion and deposition (Dollar, 2002:128).

The Department of Water Affairs and Forestry (DWAF) is the custodian of all water resources in South Africa, making it responsible for the care and management of water resources to ensure sustainable social and economic development. In 1994 DWAF launched the River Health Programme (RHP) to gather information on the health of South Africa’s river systems (RHP, 2003:4). Although DWAF guides the RHP, the programme is a co-operative venture with participants from many government and non-government organisations, namely the Department of Environmental Affairs and Tourism (DEAT), the Water Research Commission (WRC), DWAF regions, provincial government departments, universities, conservation agencies, private sector organisations and so on.

2.8.1 Geomorphology

The geomorphological processes determine the morphology of the channel which, in turn, provides the physical framework within which the steam flows. Geomorphology is therefore an important consideration in the assessment of river health (Rowntree and Ziervogel, 1999:1) and has become an important component of all stages of this process including the overall assessment of the catchment scale impacts, site selection and recommendation of flows for channel maintenance. Geomorphologists are also involved in developing relationships between channel morphology and hydraulic habitats so that onsite at–a–discharge assessments can be better extrapolated to channel reaches and to a range of discharges.

In South Africa, fluvial geomorphology has been a neglected discipline and it is only in the last decade that significant research has been initiated to study contemporary fluvial systems. An examination of South African river literature shows that it is the ecological community that has conducted most of the research on the physical characteristics of the country's rivers (Rowntree and Wadeson, 1999:2). According to Rowntree and Wadeson (1998:140), since South African geomorphologists were first invited to attend an In-stream Flow Requirements (IFR) workshop in 1992, they have become increasingly involved in developing the Building Block Methodology (BBM) used for estimating IFR. The development of BBM is a dynamic process and the refinement of geomorphological ideas developed along with it; as experience in geomorphology of South African rivers expands, so will the ability to manage them in a sustainable manner.

In South Africa the BBM for determining the IFRs is based on three groups of flows: low flows, freshes and floods. Low flows are defined as flows that have the longest duration and provide seasonal habitat for individual species (Dollar, 2000:396). Freshes are small, short–lived increases that provide essential flow variability, initiate scouring and cleansing of the riverbed, dilute poor water quality and possibly trigger the spawning of fish. Floods are substantial flow increases that cause significant bed scour, bank erosion and sediment transport, and, through over-topping the banks, provide a hydraulic link between the channel and floodplain.

According to Dollar (2000:391), the realisation that the traditional classification of systems was unsuitable for South African fluvial systems led to the development of two new classification systems. The first is the hierarchical classification system of Rowntree and Wadeson (1998). The second is the bottom-up hierarchical classification system of Van Niekerk and Heritage (1993). Both these systems emerged from the requirements of ecologists for a physical template for aquatic ecosystem management.

Rowntree and Wadeson's (1998) stream classification system provides a scale–base link between the channel and the catchment. It also allows a structural description of spatial variation in a stream habitat. This system may also be regarded as a cascading system, where each level provides input into lower levels (Dollar, 2000: 391). The Van Niekerk and Heritage (1993) system of classification points out that the geomorphology of the Sabie system reflects the response of a system to a highly variable water and sediment discharge superimposed on a macro channel controlled by the underlying geology. The implicit assumption is that there are various spatial and temporal levels at which fluvial systems operate and that they could be separated into distinct temporal scales.

The environment is conventionally accepted as a resource to be protected in South Africa and, as such, it makes a legitimate demand on the competition for limited water resources in southern Africa. This was shown in a study conducted by Heritage, Van Niekerk, Moon, Broadhurst, Rogers and James (1997) in which they showed that it is essential to quantify the requirements of the environment reliably. In the conservation of areas such as the Kruger National Park, where there is an imperative to maintain the biotic system, this is of particular concern. The role of rivers has been highlighted as playing a significant part in the functioning of the riparian system.

In the study carried by Rowntree and Dollar (1996:20), in the Bell River, Eastern Cape, the results indicate that the two primary spatial controls on channel form and pattern are riparian vegetation and bed-material size. Evidence indicates that narrow, stable stretches are associated with finer bed materials and relatively high levels of riparian vegetation. Riparian vegetation increases bank stability and reduces cross-section, thereby inducing stability at flows less than bankfull. However, at flows greater than bankfull, reduced channel capacity results in frequent flooding which may alternatively lead to channel avulsion.

2.9 SUMMARY

Over many decades there has been a change in the attitude toward the physical management of rivers (that is, of hazards such as flooding and erosion) from one of dominating and controlling nature to considering the dynamic character of fluvial systems. This has come about owing to the collaboration between fluvial geomorphologists and river engineers in providing sustainable solutions to the problems of flooding and erosion. The shift is from providing hard management strategies (concrete walls) to soft management strategies.

There has been an increasing interest in the role of vegetation in fluvial geomorphology in recent years because it has been recognised that river dynamics cannot be fully understood without taking into account the impact that vegetation, both on the banks and within the channel, has on bank stability. Well-vegetated banks are some 20 000 times more resistant to erosion than similar bank sediment without vegetation. The species of trees and the type of under-story vegetation can all influence bank erosion rates.

The stability of the river bank depends on the balance of forces, motive and resistance associated with the composition and strength of bank material, vegetation cover, local channel form and organic debris dams, the stream hydrological regime, the role of ground water and antecedent soil moisture.

Bank material characteristics are a significant sedimentological control on the strength and stability of channel banks and therefore on the adjustment of channel width.The highest rates of bank erosion are known to occur because of high flows during prolonged wet periods, rather than simply by the largest storms or floods.

CHAPTER 3

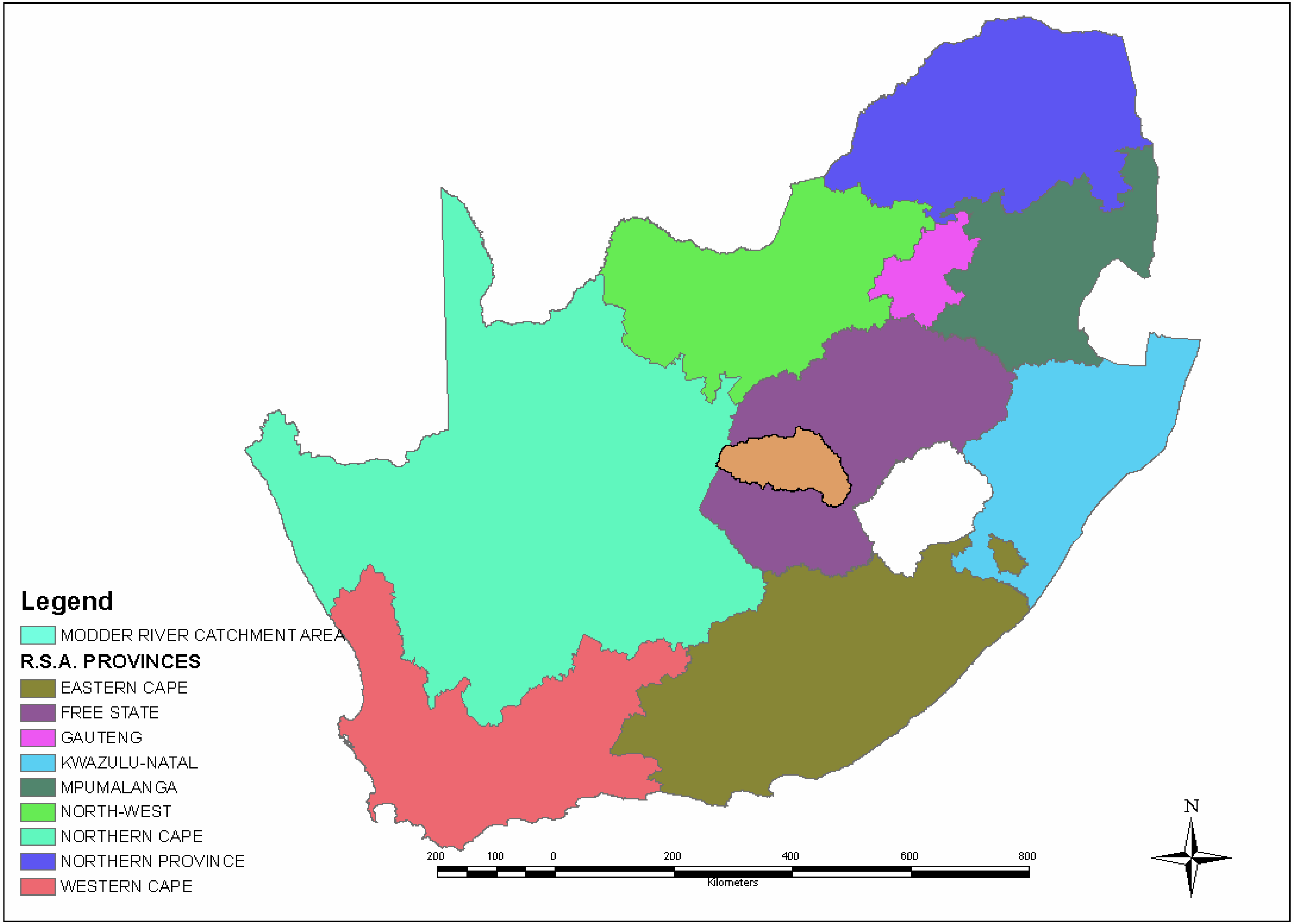
DELINEATION OF STUDY AREA

3.1 LOCATION

The major part of the Modder River catchment area is situated in the southern central Free State Province with a lesser part in the Northern Cape Province (Figure 3.1). The catchment comprises an area of about 17 360 km^2 (Midgley *et al*, 1994b). The Modder River has its source near Dewetsdorp, flows in a north-westerly direction and then turns in a westerly direction until it joins the Riet River at Ritchie (Raper, 1987:223; Seaman *et al.*, 2001:15).

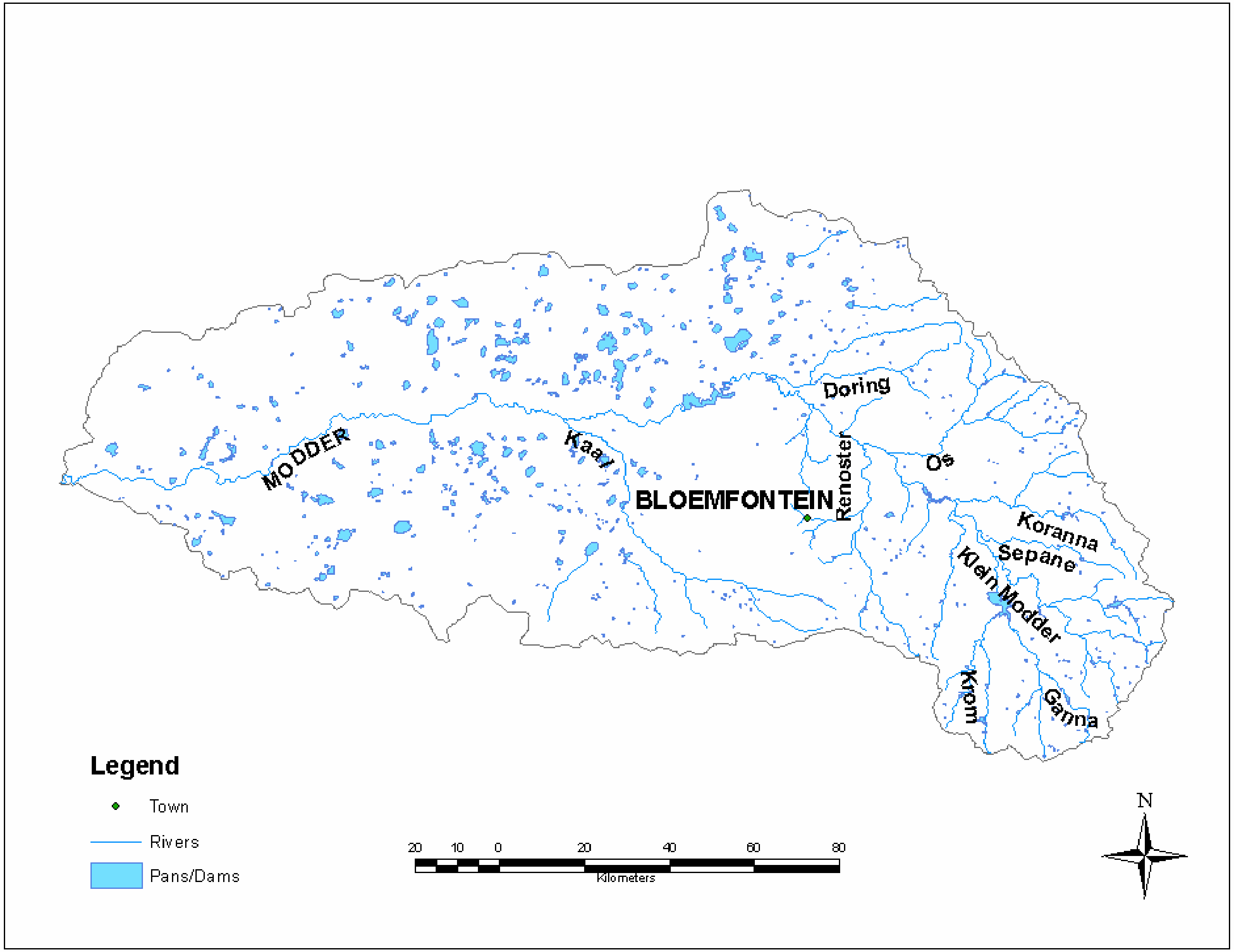
The main tributaries that drain into the Modder River are the Kaal, Os, Doring, Renoster, Koranna, Sepane, Klein Modder and Krom Rivers and the Gannaspruit (Figure 3.2). There are three major dams along the main course of the Modder River, *viz*. Rustfontein, Krugersdrift and Mocke's Dam. Accourding to Midgley *et al.*, (1994a) most of the natural runoff (50mm) into the Modder River is from above the confluence of the Modder and Klein Modder Rivers.

Below the Krugersdrift Dam the river flows through an area of very low gradient where numerous pans are found. In the summer months these pans are filled after rainfall but they hardly ever overflow (Figure 3.3), therefore contributing very little (2,5mm) to the runoff into the Modder River (Midgley *et al.*, 1994b). The Modder River plays a significant role in supplying water for domestic, agricultural and industrial use in the Bloemfontein, Botshabelo and Thaba N'chu areas. According to the present estimates by Seaman *et al.*, (2001:16), the Modder River is exploited to its full capacity.



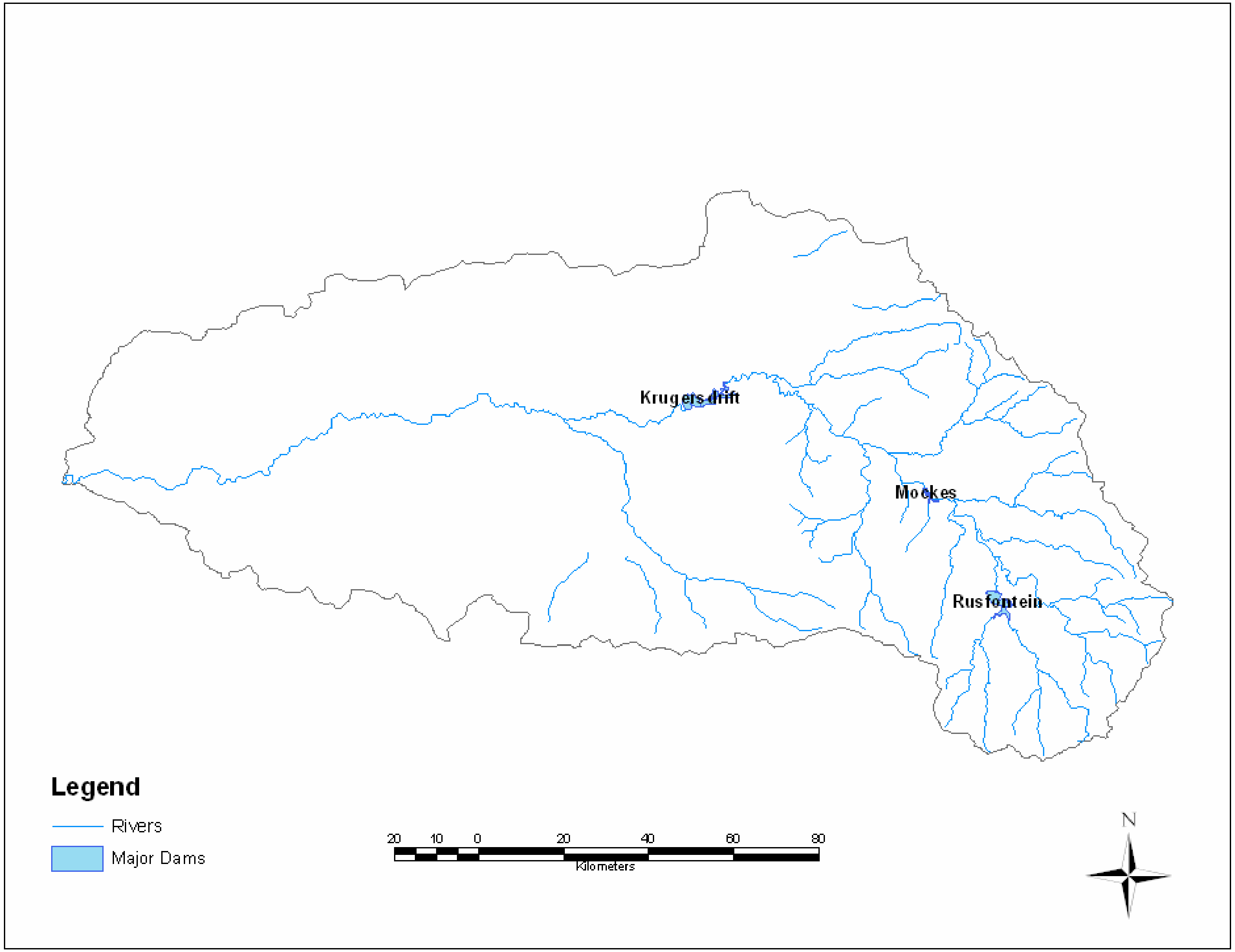
Source: DEAT, 1999

Figure 3.1: The location of the Modder River catchment



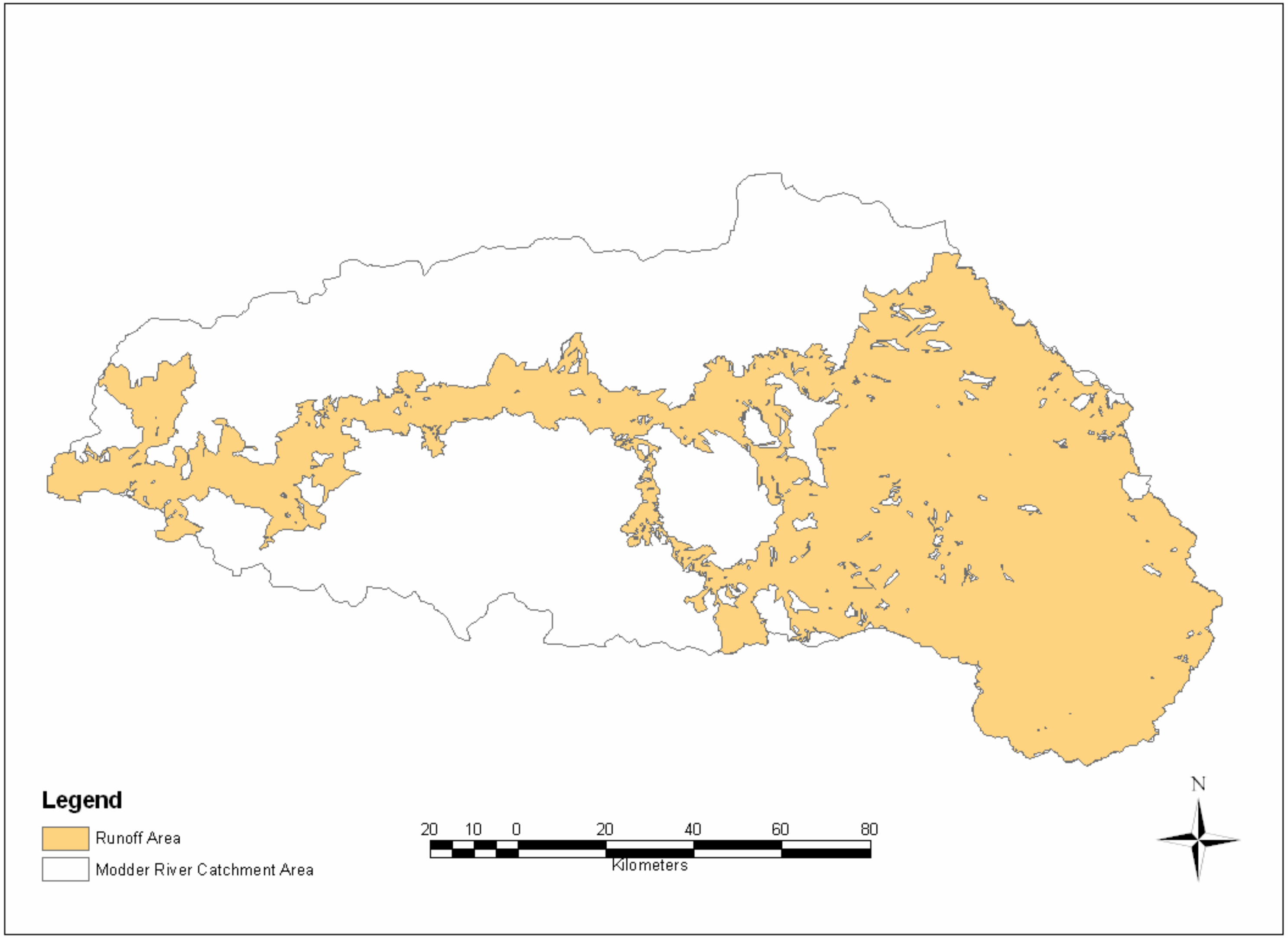
Source: DEAT, 2001

Figure 3.2: The Modder River drainage



Source: DEAT, 2001

Figure 3.3: The major dams along the Modder River



Source: Barker, 2002:19

Figure 3.4: The area that generates surface runoff tof the Modder River

3.2 RAINFALL AND EVAPORATION

The highest rainfall occurs during January to March and the lowest during June to August. The average annual rainfall is 550mm, with the average in the east near Thaba N'chu being 650mm and in the west towards Ritchie, 400mm (Midgley *et al.*, 1994a). The most important factor of the rainfall in this area is its variability and unpredictability. The Modder River has a mean annual runoff of 184×10^6 m^3. The annual evaporation rate at Dewetsdorp where the Modder River originates, is 1 500mm per year and where the Modder River and Riet River converge, it is 2 100mm per year (Midgley *et al.*, 1994a). Evaporation therefore increases from east to west as opposed to rainfall that decreases from east to west (Midgley *et al.*, 1994a).

3.3 SOIL AND FARMING

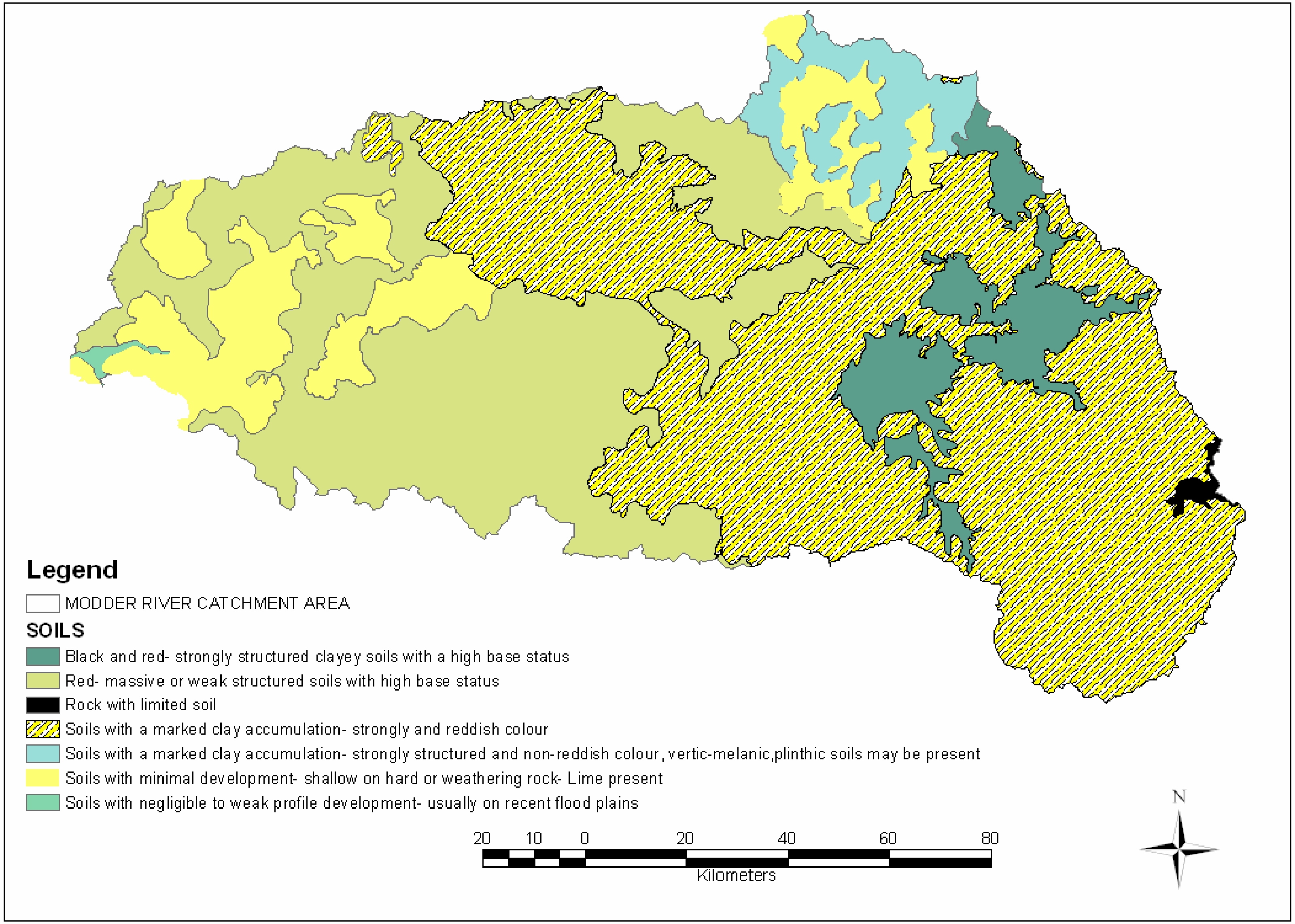
Soils in the area vary from moderate to deep clayey loams found in the exceptionally flat central region of the study area (Figure 3.5). In the western part of the catchment the soil has a light texture (DWAF, 1999). This could be because large amounts of sediment are transported into the area by westerly winds. In the middle section farming is mostly dairy and mixed farming (wheat and maize) with sheep farming in the southeast. Land use in the area is predominantly urban (formal and informal) and irrigated agriculture. The land cover of the Modder River is mostly grassland (Figure 3.8).

3.4 GEOLOGY

The geology of the Modder River catchment consists mainly of rocks of the Karoo Sequence, interspersed in places with dolerite dykes (DWAF, 1999) (Figures 3.6 and 3.7). Most of the study area has outcrops of the Beaufort Formation belonging to the Karoo Sequence. This formation consists of Intercalated Arinaceous (sandstone) and Argillaceous (mudstone) strata in the west (Figure 3.7).

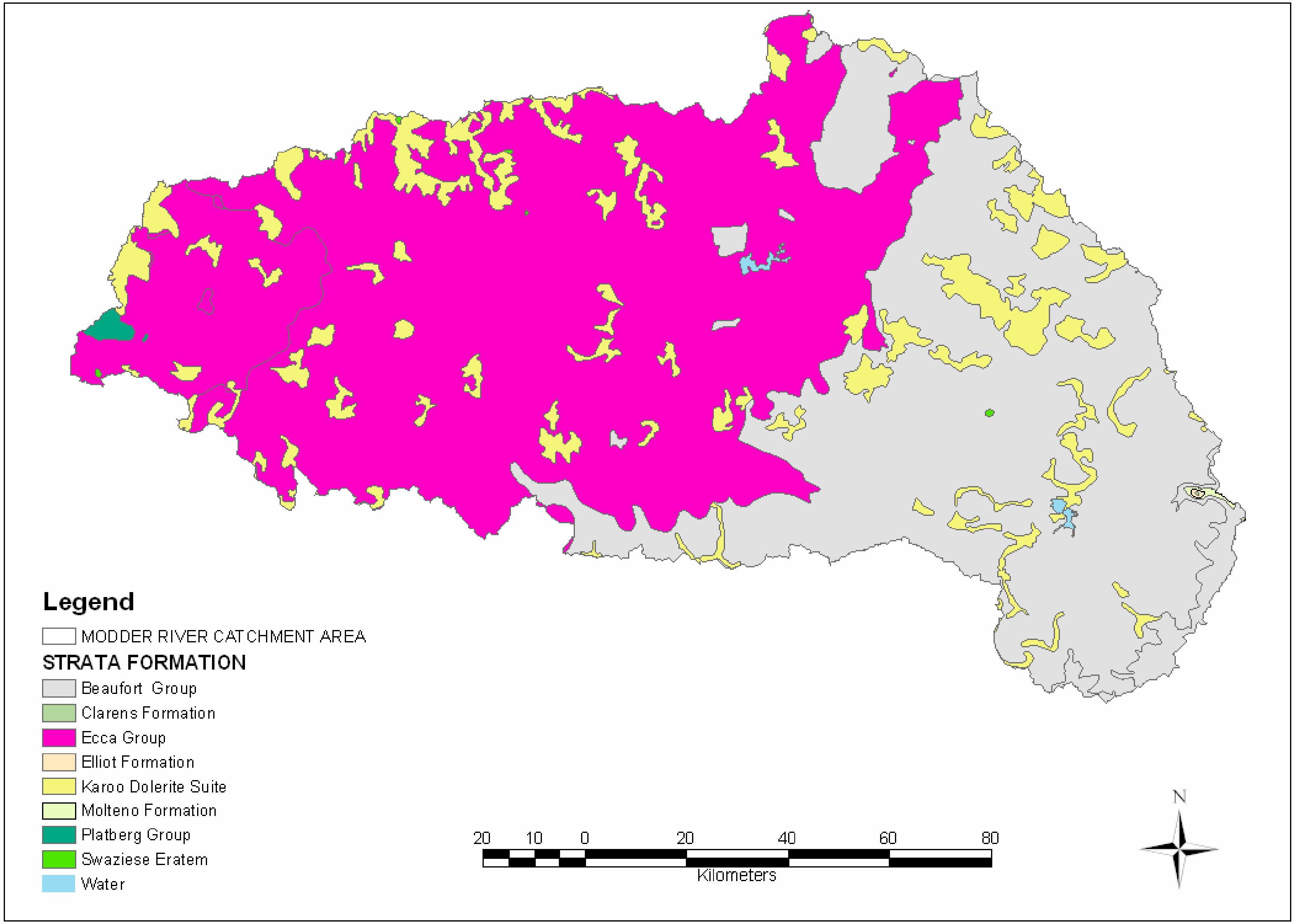
3.5 SUMMARY

The Modder River catchment has a sound dendritic drainage pattern in the eastern part, while the western part is dominated by a number of pans. This catchment also has a higher rainfall in the eastern than the western part. The most important rainfall factors in this area are variability and unpredictability. Soils in the area vary from moderate to deep clayey loams found in the exceptionally flat central region of the study area.



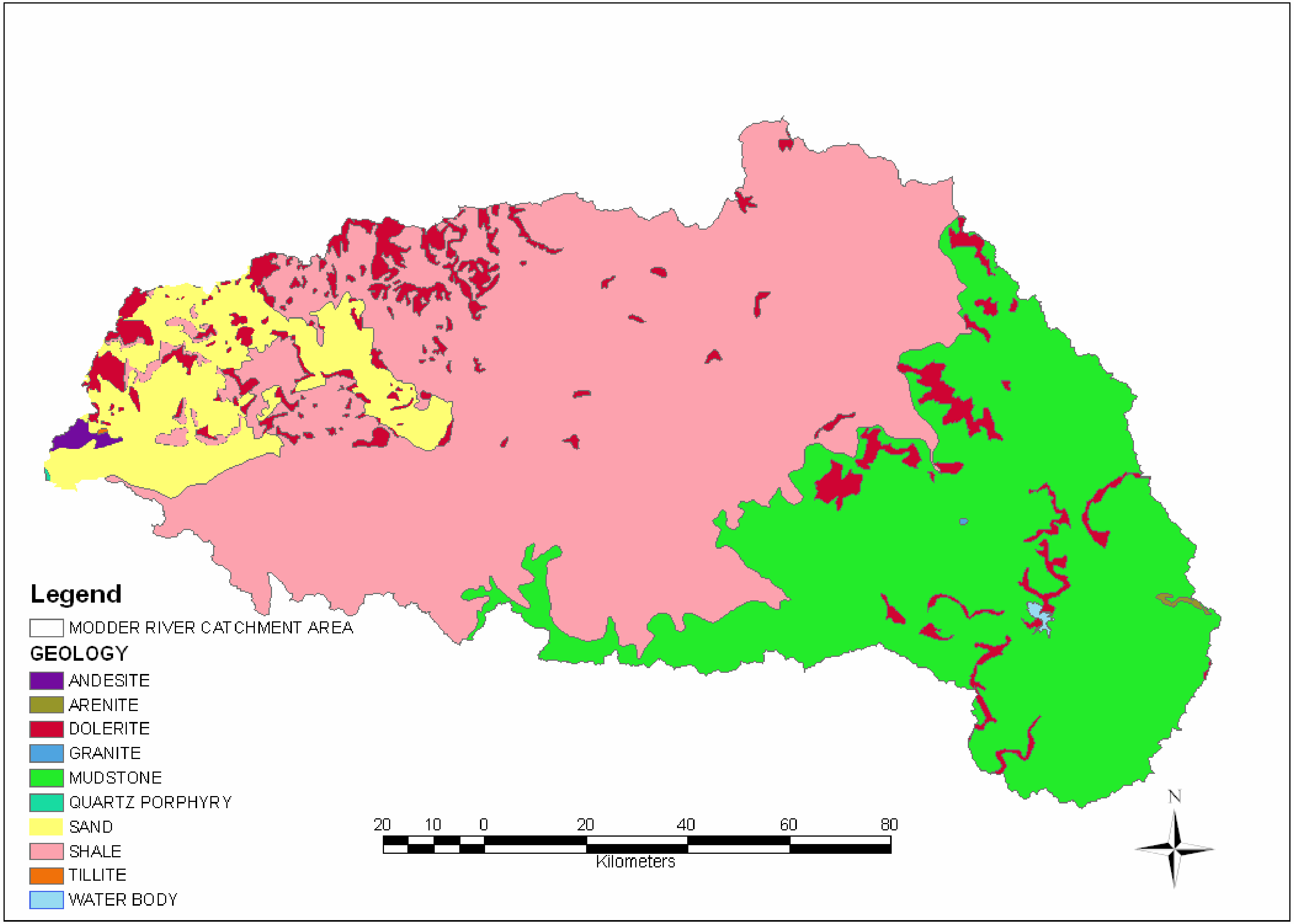
Source: DEAT, 2001

Figure 3.5: Soils in the Modder River catchment



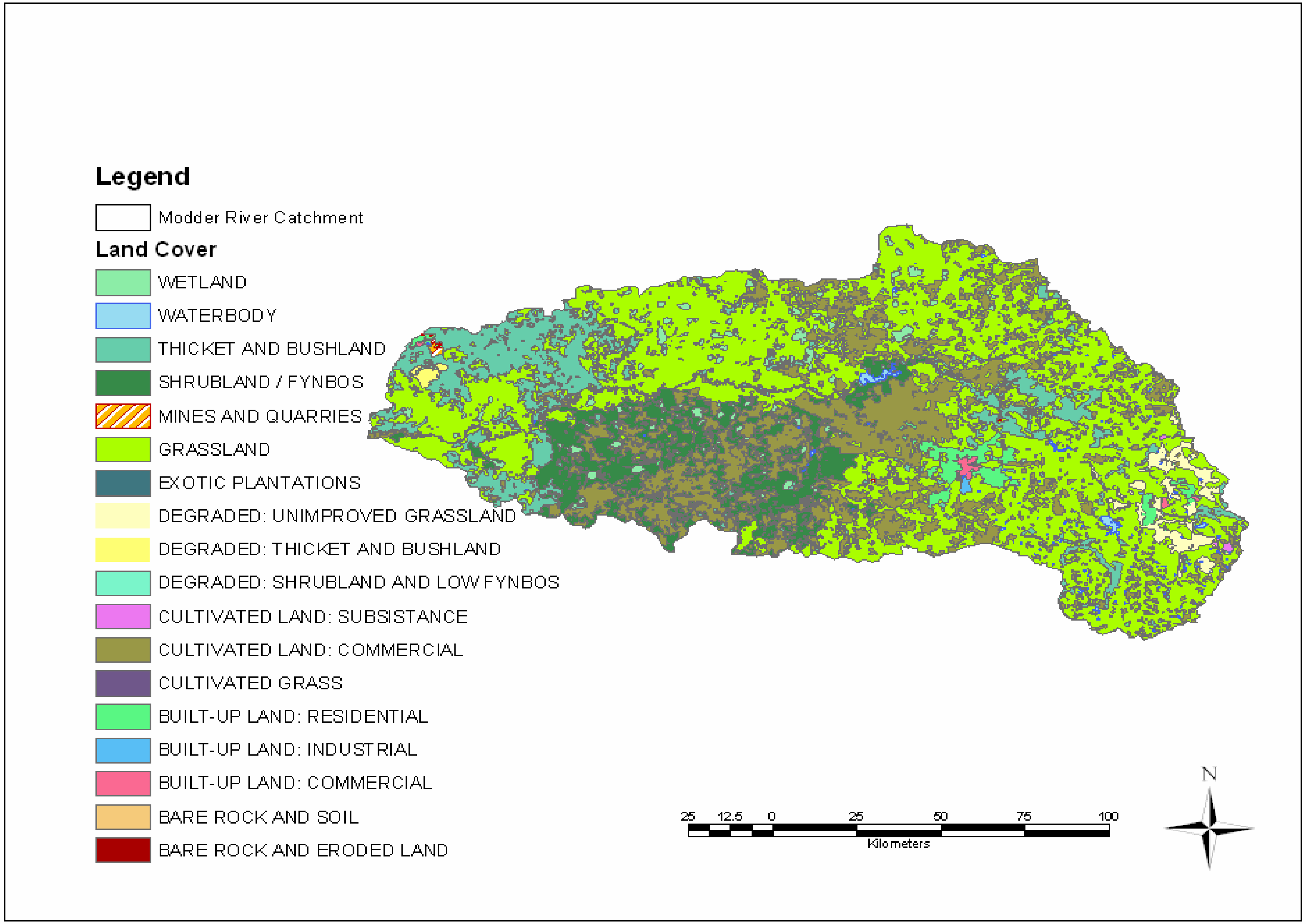
Source: DEAT, 2001

Figure 3.6: Strata/land formations of the Modder River catchment



Source: DEAT, 2001

Figure 3.7: Geology of the Modder River catchment



Source: DEAT, 2001

Figure 3.8: Land-cover of the Modder River catchment

CHAPTER 4
METHODOLOGY

The banks of the Modder River are the likely source of sediments into the main course of the river. The Modder River catchment area has an endoreic character in the western part (refer to Figure 3.4, Chapter 3) where the Modder River flows through an area of very low gradient with numerous pans (Barker, 2002). Surface drainage in this part is poorly developed; even in exceptionally high rainfall events (as in 1988) it reveals no connectivity between pans and the main streams.

4.1 VARIABLES

Riverbank processes consist of the detachment of grains or assemblages of grains from the bank surface. The rate of riverbank processes depends on the balance of forces, motive and resistance associated with the bank material composition and strength, vegetation cover, local channel form and dams, the stream hydrological regime, the role of ground water and antecedent soil moisture. Therefore, the spatial variability of bank-forming material, vegetation cover and type, as well as the channel form (width : depth ratio) were investigated to realise the aim of the present study.

The silt/clay content of the soil in the bank material has long been recognised (Schumm, 1977:108; Knighton, 1987:71) as influencing fluvial erosion and mass failures; the resistance of a bank to both processes tends to increase with increasing silt/clay content, as silt/clay particles are much more difficult to erode because of the grain-to-grain cohesion, largely absent in sand.

According to Lawler *et al*. (1997:154), the results of recent research indicate that the potential impact of bank vegetation on the overall flow capacity of the channel is strongly related to the width : depth ratio; vegetation resistance on the banks is only significant in channels with width : depth ratios of less than 12. The effects of vegetation are probably greatest on small rivers (Lawler *et al*., 1997:154; Eaton and Miller, 2004: 41).

Vegetation can either increase or decrease bank stability, depending on the type of vegetation, bank geometry and bank material (Stott, 1997:396).

4.2 METHODS

A helicopter and fieldwork surveys were conducted to obtain the required materials for this study.

4.2.1 Helicopter survey

Photographs and video recordings were used for detecting morphological characteristics on thirty-six 5km segments on the Modder River. Photographs and videotape recorded the spatial relationship of landforms and provided three-dimensional information and supplementary details useful for interpreting the erosion rates or patterns of the banks, bank gullies and vegetation cover, as well as the location of weirs and dams. Collins and Walling (2004: 170) consider the collection of data via photographs and video recordings as an alternative to expensive fieldwork. They also provide a means of archiving information.

A videotape made by the CEM during a helicopter survey on 25 and 26 January 2003 was used as a source of data to assess the densities of the riparian vegetation, and gully and bank erosion, as well as pinpointing the location of impoundments on the Modder River. The videotape was originally intended to assess the habitat integrity of the Modder River. Prior to the aerial survey, the river was divided into numbered 5km segments on 1 : 250 000 topographic maps. The co-ordinates of 36 segments were stored on a global positioning system (GPS) and used by the navigator to inform the observers when the helicopter moved into specific 5km segments. The survey was conducted in a downstream direction at an altitude of between 50 to 100m and the flight path followed the left bank of the river to enable the camera operator to record information on both river banks and the total width of the stream channel.

In addition to the helicopter survey, a fieldwork survey was conducted to supplement the aerial observations (Figure 5.2).

4.2.2 Fieldwork survey

Twenty-one sites (Figure 5.3) along the Modder River were investigated; global positioning system (GPS) was used to pinpoint the positions of each site in terms of latitude, longitude and height above sea level. Bank sediment samples were extracted from each site. An attempt was made to take sediments removed from the water as some particles might be washed away as samples were being taken out of the water. Photographs of every site were taken to record their characteristics; an attempt was made to take clear overhead shots to show a plan view looking up- and down-stream, including the riverbanks. Then sediment samples were taken to the laboratory to determine sediment particle size distribution.

The cross-sections of ten sites (Figure 5.11) along the Modder River were measured using an A-frame and a clinometer as shown in Plate 4.1.

Fieldtrip, March 2005

Plate 4.1: Measuring a cross-section using a clinometer and the A-frame (MRS 1)

4.3 DATA COLLECTION

After viewing the tape, information on river characteristics on the thirty-six 5km segments along the Modder River was transcribed for every segment (Table 4.1).

4.3.1 General characteristics

General river characteristics observable from the air were weirs/dams, bank erosion, gully erosion, riparian vegetation and tributaries.

Table 4.1: General river characteristics recorded for each 5km segment

Characteristics	Description of categories
Segments	Longitude and latitude
Weirs and impoundments	Longitude and latitude
Bank erosion	Bank collapse, accentuated stream bends, exposed tree roots, very steep banks/free of vegetation and for building purposes
Gully erosion	Density and sizes of bank gullies
Riparian vegetation	Density and type of vegetation (grasses, bushes and trees)
Tributaries	Number per segment

4.3.2 Sediment sources and gully sizes

Weights were assigned for bank collapse, accentuated stream bends, exposed tree roots, very steep banks/free of vegetation and for building purposes, as well as bank gully sizes (sediment source variables) based on their potential for delivering sediments into the main course of the Modder River (Tables 4.2 and 4.3). The variables listed in Tables 4.2 and 4.3 were identified as the most dominant sediment sources in the 5km segments. The sum of the variables observed gave the total weight of gully erosion and bank erosion in every segment.

Table 4.2: Identification of sediment sources and their assigned weights for bank erosion

Identification	Weight
Steep banks/vegetation free	1
Exposed tree roots	1
Accentuated stream bends	2
Sand mining	3
Bank collapse	4

Table 4.3: Gully sizes and their assigned weights of sediment source

Gully size (approx. depth and width) m	Weight
<1	1
>1	2
2	3
3	4
4	6

4.3.3 Vegetation assessment

The assessment of the densities of vegetation was based on four descriptive classes with ratings from **1:** ***Clear*** (grass, with no bushes or trees), **2:** ***Patched*** (grass and bushes), **3:** ***Dense*** (grass, bushes and trees) to **4:** ***Very Dense*** (bushes and trees) (Eaton and Miller, 2004:40) for every 5km segment.

4.3.4 Bank erosion and gully assessments

The assessments of densities of bank erosion and gullies (300m from the channel) were based on six descriptive classes with total sediment weight ratings from **1 to 5** (***Small***), **6 to 10** (***Moderate***), **11 to 15** (***Large***), **16 to 20** (***Serious***), **21 to 25** (***Critical***) and **greater than 25** (***Very critical***) according to Kleynhans's (1996:44) approach for every 5km segment.

4.3.5 Channel cross-section survey

The cross-sectional shape of the Modder River was measured at ten sites using an A-frame and clinometer (see Figure 4.1), where the bank angles are below 60° (Goudie, 1990). To measure bank slopes (Q) with respect to the horizon, a clinometer was used for every h (h = 3 metres, the length of the A-frame) across every reach perimeter, assigning positive values to angles down the slope and negative values to angles up the slope of the bank.

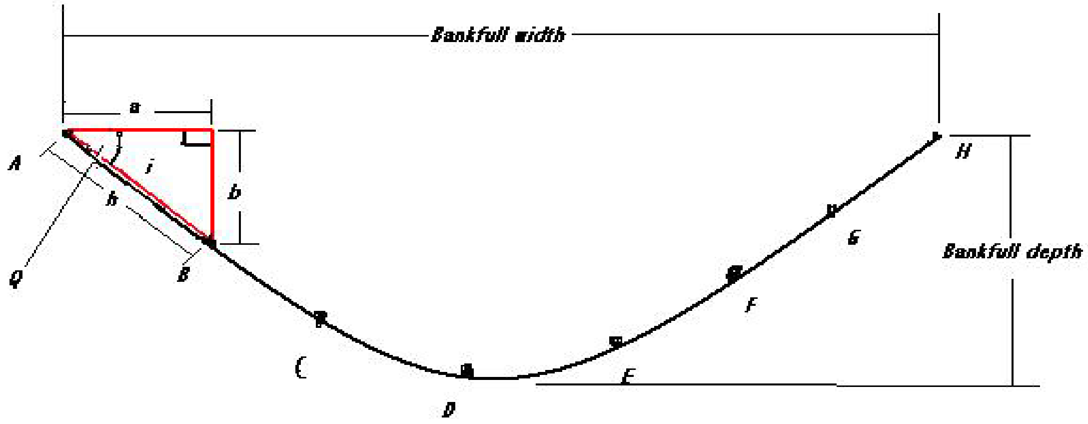


Figure 4.1: A sketch of a surveyed cross-section using an A-frame

4.4 DATA ANALYSIS

Data obtained were analysed using statistical, laboratory and GIS methods.

4.4.1 Statistical analysis

Field survey data from the A-frame and clinometer (lengths and angles) were entered into a Microsoft Excel document to define the channel as a set of co-ordinates with arbitrary, equally spaced perimeter sections surveyed to calculate successive widths and depths (Goudie, 1990). From Figure 4.1:

Q_i - is the angle between the horizon and perimeter section, where ***i*** is an arbitrary section (angles were converted to radii for use in Microsoft Excel).

a - is the section of the bankfull width, where all a's are summed to give the bankfull width.

b - Is the section of the bankfull depth, where some b's are summed to give the bankfull depth for positive or negative angles.

h – is the length of the A-frame: sections AB, BC, CD, DE, EF, FG and GH are equal to h_i and their summation gives the channel perimeter.

The lengths of a_i and b_i were calculated by the Pythagorean theorem for right-angled triangles as:

$$a_i = hCosQ_i \quad \ldots\ldots (1)$$

$$b_i = hSinQ_i \quad \ldots\ldots (2)$$

Bankfull width (w):

$$w = \sum_{i-1}^{n} a_i \quad , \ldots\ldots (3)$$

where n is the total number of sections.

Bankfull depth (d):

$$d = \sum_{i-1}^{n} b_i \quad , \ldots\ldots (4)$$

where Qi is only positive or negative angles and ***n*** all positive or negative sections.

Point A from Figure 4.1 is the reference point (0, 0), the co-ordinates of point B along the channel perimeter were given as (a_i, b_i). For the rest of the points, C, D, E, F, G and H, their co-ordinates are the summation of the successive co-ordinates of previous points from A, as **(**$\sum_{i-1}^{n} a_i$ **,** $\sum_{i-1}^{n} b_i$ **)**. Plotting points A to G gives the cross-sectional profile of every channel reach.

4.4.2 Laboratory analysis

Particle size distribution of the bank material was determined from laboratory analysis: clay (0,002mm), fine silt (0,02mm), coarse silt (0,05mm), very fine sand (<0,106mm), fine sand (0,106mm), medium sand (0,250mm) and coarse sand (0,5mm) by using wet sieving method.

4.4.3 Geographic information systems (GIS)

Geographic Information Systems (GIS) provide an ideal tool for environmental planning as they make use of the capabilities of modern, high-speed computers to store large amounts of environmental data in a geographical format, manipulate data according to some model of environmental processes and are able to display the results in pictorial form (Coroza *et al*., 1997:14). Attempts are being made to apply GIS to many areas of environmental planning and management by linking the GIS with appropriate dynamic models of the environmental processes concerned. Without these models, the GIS can go no further than static spatial modelling. Moreover, Coroza *et al*. (1997:14) note that even though we are able to link models of environmental processes with GIS, unless the required environmental data can be acquired in digital form at reasonable cost and at a suitable scale, such integrated systems are useless.

GIS-based approaches provide one of the few means available for systematically examining the role of spatial variability of sediment sources in the evolution of the Modder River landscape. The spatially explicit nature of GIS analyses and the GIS emphasis on incorporating real-world data combine to make GIS a powerful tool for building insight into the evolution of complex landscapes and landscape processes (Finlayson and Montgomery, 2003:148).

ArcView 8.3 Desktop GIS was used for the analysis, processing and representation of data. The digital base maps were obtained from the Environmental Potential Atlas for South Africa (DEAT) (2001). These maps were supplied in (or converted to) Albers's equal area projection with the Hartebeesthoek94 Datum (WGS84 ellipsoid) in the form of shapefiles [*.shp – in which spatial components are saved in the form of point, line or surface phenomena (features)].

The co-ordinates of the thirty-six 5km segments from a GPS were used to create a GIS master database stored in Microsoft Excel in the form of latitudes and longitudes. The co-ordinates were then exported to ArcView 8.3 Desktop GIS as points (x, y) and overlaid with the DEAT data to demarcate the beginning and the end of each segment. The helicopter path along Modder River was then extracted from the points from the rest of the river to create a new shapefile. Using Arcmap Editor, this shapefile was split into thirty-six segments with regard to the beginning and the end of every segment. Forming a 300m buffer around each segment created another shapefile. This shapefile was merged with the descriptive classes of the segments to show their respective densities and spatial variability by using different colours on maps. The resultant shapefiles were overlaid with the shapefiles of land-cover (land use), strata formation, precipitation, evaporation, soils and geology in the Modder River catchment in order to determine their influence on spatial variability of riparian vegetation, bank gullies and bank erosion.

The co-ordinates of the weirs and dams from a GPS were also used to create a GIS master database stored in Microsoft Excel in the form of latitudes and longitudes. The co-ordinates were then exported to ArcView 8.3 Desktop GIS as points (x, y) and overlaid with the DEAT data to pinpoint the orientation of weirs along the helicopter survey path.

4.5 LIMITATIONS

Three main limitations were experienced in collecting the materials for this study. Firstly, the helicopter survey did not cover the entire length of the Modder River, the reason being the lack of the necessary funding or sponsorship for financing another helicopter survey to cover the remaining parts of the Modder River. Secondly, the luxuriant growth of vegetation along the Modder River banks limited detailed observation of bank erosion. Finally, sediment samples could not be obtained from sites in all thirty-six segments because access to private land was unobtainable from the owner of the proposed sites. Absent owners could not be contacted.

The videotape was viewed three times and for each time the information on river characteristics on the thirty-six 5km segments along the Modder River was transcribed. The records were then compared and averaged to validate the results.

4.6 SUMMARY

Helicopter and fieldwork surveys were carried out to obtain the materials for this study. The videotape was viewed to rank the densities of riparian vegetation cover, bank and bank gully erosion and to pinpoint the locations of impoundments in the thirty-six 5km segments along the Modder River. Fieldwork surveys provided information on the sites: the channel dimensions, photographs and sediment samples. Microsoft Excel and ArchView 8.3 desktop GIS were used for data analysis and in interpreting and presenting the results.

CHAPTER 5
RESULTS

5.1 INTRODUCTION

The results of this study are presented in the form of maps, photographs, graphs and the measurements of sites and segments which were observed for proposed geomorphological analysis, percentages of silt/clay content in the bank- forming material, riparian vegetation cover, bank erosion, gully erosion, impoundments as well as channel dimensions in relation to drainage basin area. Locations of the 5 km segments are shown in Figure 5.2.

5.2 SILT/CLAY CONTENT

The percentage of silt/clay content along the Modder River banks is quite low at around 30% (Figure 5.1 and Appendix B). The banks are therefore classified as non-cohesive. Low silt/clay content is linked to wide, shallow cross-sections. The Modder River consists mostly of coarse-grained sediment load. Site MRS22 has silt/clay content at sixty percent. This shows a narrow, deep cross-section. Site MRS11, situated below the Krugersdrift Dam, shows the lowest silt/clay content at 15%. Below this site the silt/clay content increases slightly. The resistance of a bank to both bank failure and fluvial entrainment increases with more silt/clay content. The results indicate that the Modder River banks have a low resistance to erosion.

Non-cohesive materials are relatively coarse-grained and are usually well drained. Observations of erosion of cohesionless banks make it clear that particles in the sand and gravel size range are highly susceptible to erosion by fluvial entrainment. The stability of a non–cohesive bank also depends on the angles of the slope.

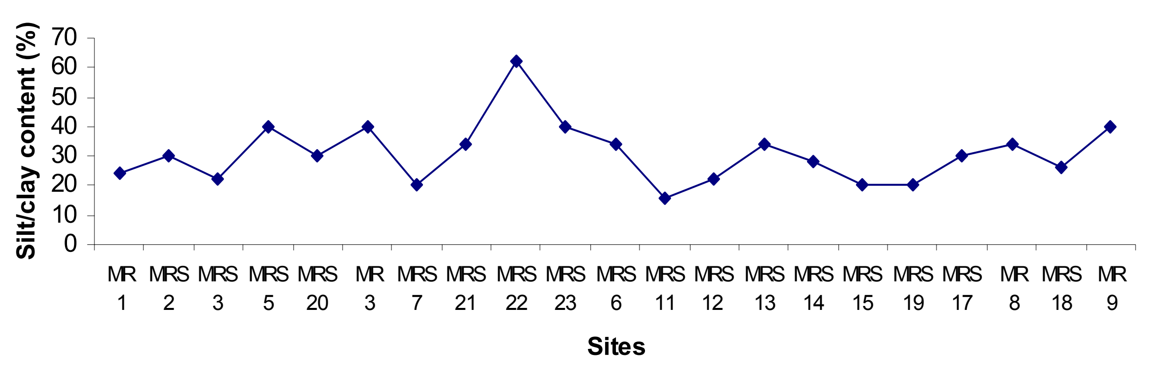
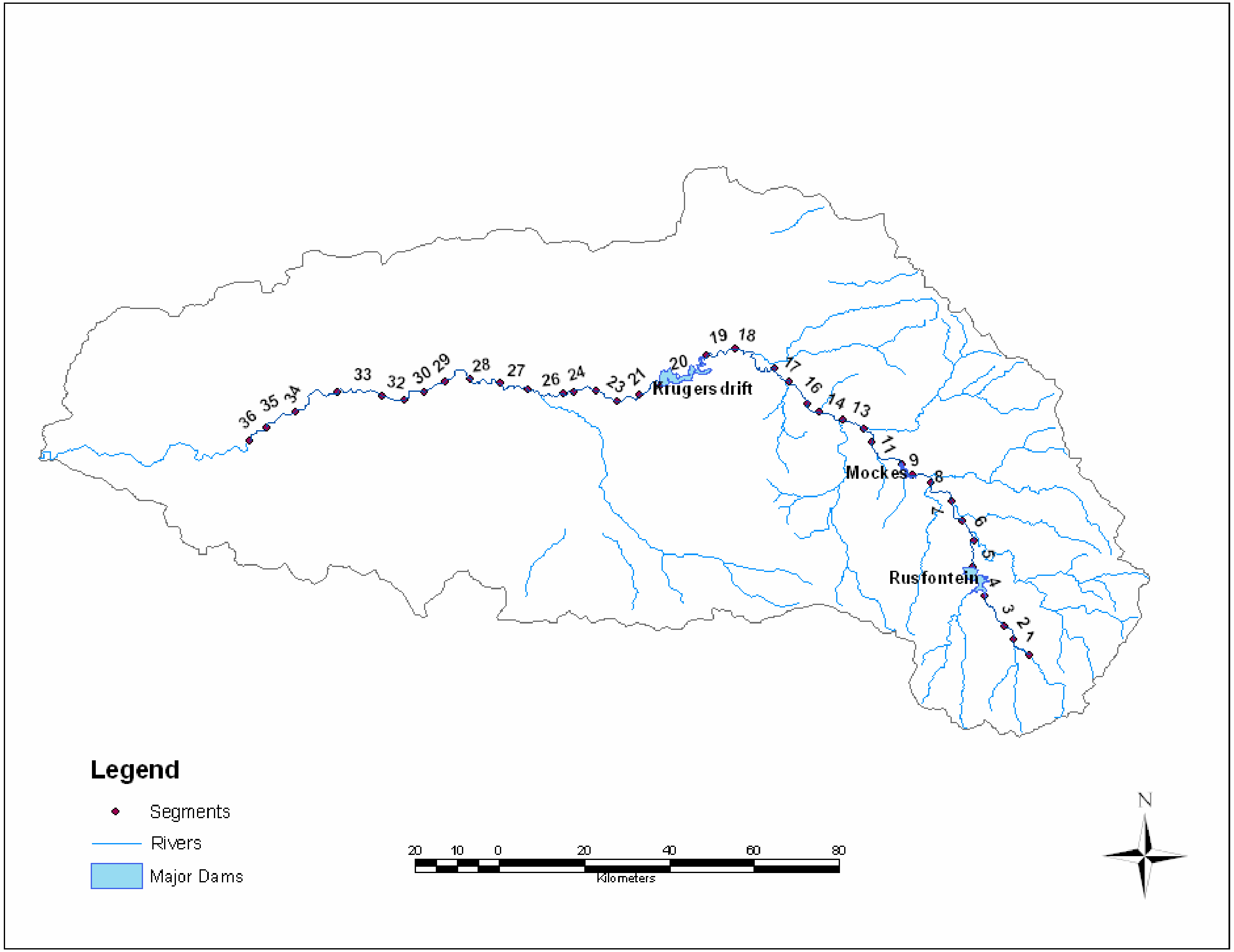


Figure 5.1: Silt/clay content along the Modder River

5.3 RIPARIAN VEGETATION

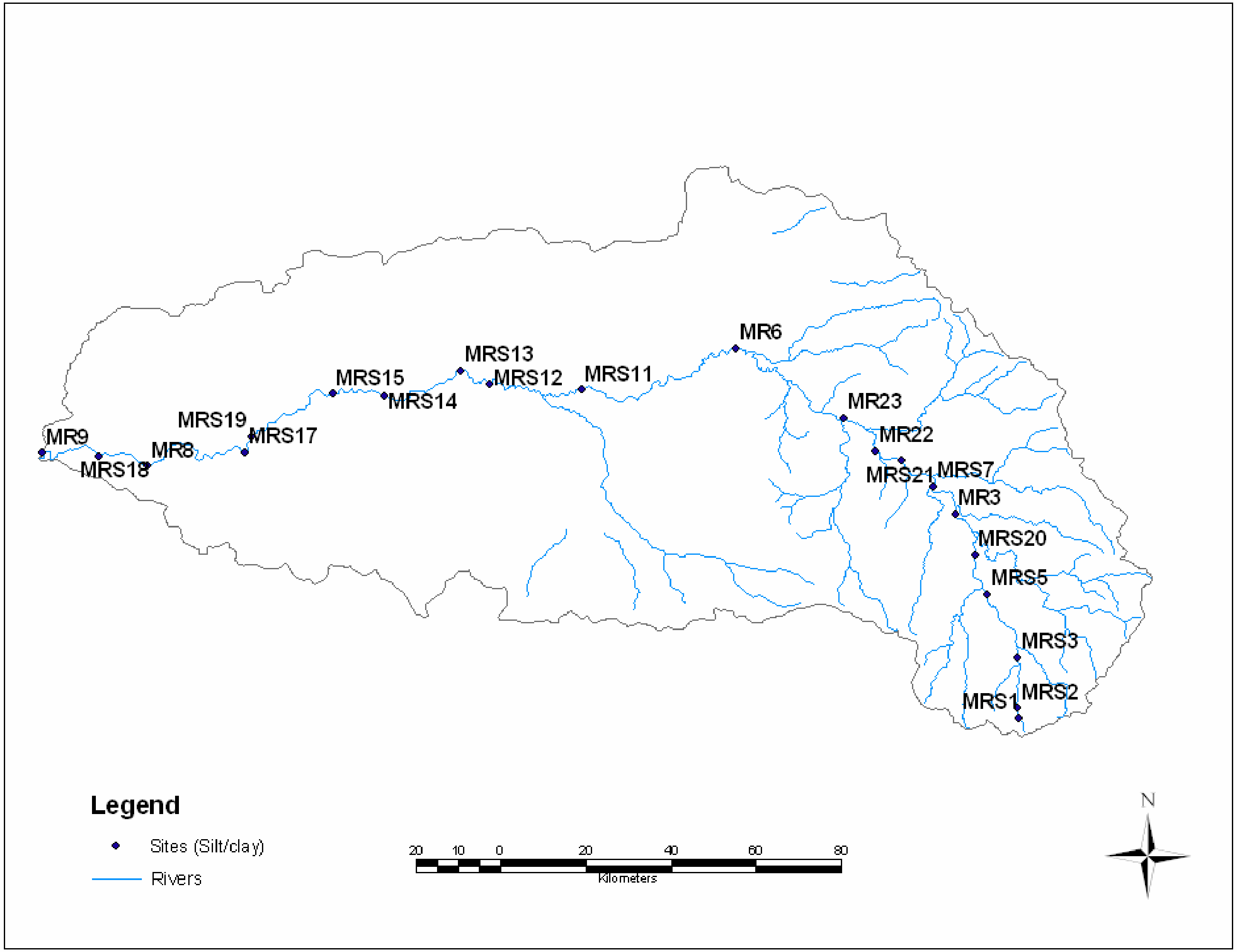
Plant cover reduces frost susceptibility and thereby increases bank stability. Figure 5.4 shows the spatial variation of riparian vegetation cover along the Modder River. This figure shows that most of the Modder River banks are covered with bushes and trees (classified as **4** that is ***Very dense***) and grasses, bushes and trees (classified as **3** that is ***Dense***, see Plate 5.1). There are also prominent segments covered with grasses and shrubs (classified as **2** that is ***Patched***, see Plate 5.2). There is only one segment covered with grass (classified as **1** that is ***Clear***, see Plate 5.3), that is segment 1 some kilometres below the source of the Modder River (Figure 5.2).

Vegetation protects banks by creating a lower velocity buffer between the soil and the erosional forces of the main current. Dense roots can reinforce and protect banks in a rip-rap fashion. Periodic floods of varying magnitude, variation in flow duration and sediment erosion/deposition dynamics affect vegetation patterns in various ways. Some of the most influential effects include the creation of new areas, such as point bars and depositional islands, regime-related variation in bank stability, formation of a gradient of flood intensities along channels, sediment size variation and the formation of water-availability gradients across a flood plain.



Source: DEAT, 2001

Figure 5.2: Locations of 5km segments



Source: DEAT, 2001

Figure 5.3: Twenty-one sites sampled for silt/clay content along the Modder River

With respect to Figure 5.3, there are thirteen segments classified as being congested with vegetation cover. These segments might be source of dropping large woody debris into the Modder River, as shown in Plates 5.4 and 5.5 where dead logs occupying the stream channel cause channel constriction. In segment 4 (Rustfontein Dam), segments 19 and 20 (Krugersdrift Dam) and segments 14 and 30 (presence of weirs) vegetation cover is classified as **2: *Patched***. As these segments contain a high moisture content, they could be expected to be congested with vegetation, but during high flows, the dams/weirs retreat, possibly destroying vegetation.

Fieldtrip, March 2005

Plate 5.1: Vegetation cover (class 3) classified as *Dense* (grasses, bushes and trees)

Fieldtrip, March 2005

Plate 5.2: Vegetation cover (class 2) classified as *Patched* (grasses and bushes)

Fieldtrip, March 2005

Plate 5.3: Vegetation cover (class 1) classified as *Clear* (grass, with no bushes or trees)

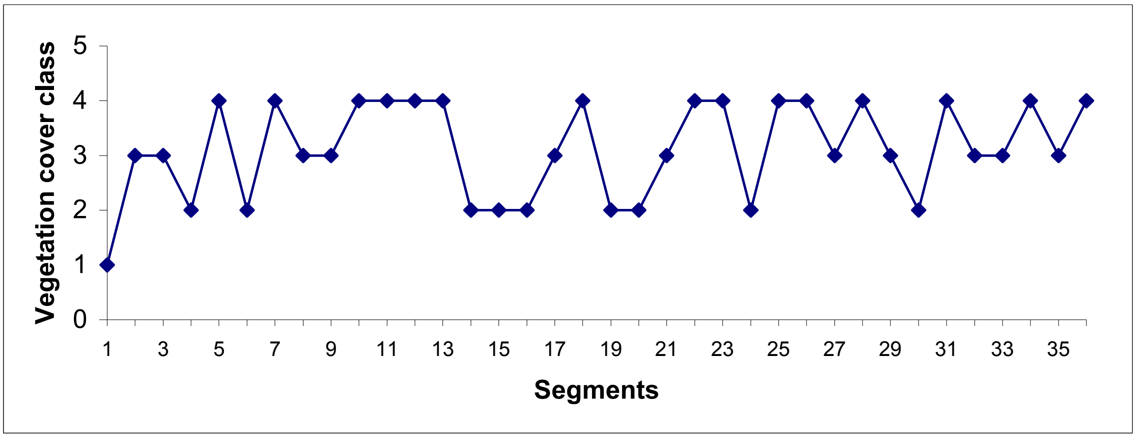


Figure 5.4: Spatial variations of riparian vegetation cover along the Modder River

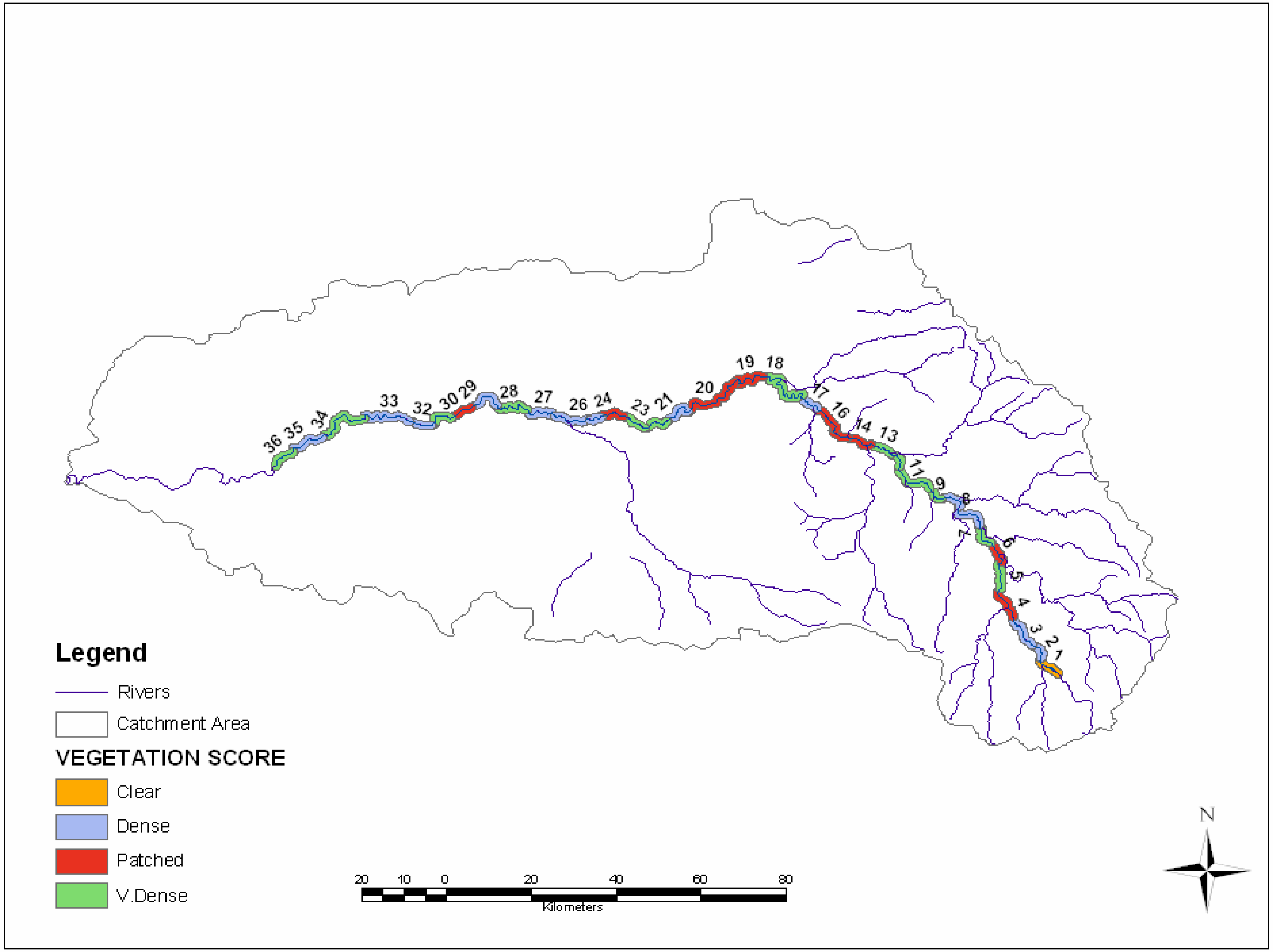


Figure 5.5: Riparian vegetation scores for every 5km segment

Fieldtrip, July 2003

Plate 5.4: Stream channel with dead logs

Fieldtrip, July 2003

Plate 5.5: Flow of the stream blocked by woody debris in a culvert (MRS 11)

5.4 BANK EROSION

Bank erosion along the Modder River is not particularly active, owing to the effect of high vegetation cover on those banks. Erosion is only minimal along acute bends along the river. Segment 16 has a high potential of becoming a high sediment source because of sand mining in the area (Figues 5.6 and 5.7). In segments 1, 2 and 3 animals trampling the bank sides cause bank erosion. The observations indicate that the most dominant type of erosion along the Modder River is gully erosion.

Fieldtrip, March 2005

Plate 5.6: Bank erosion on some segments on the Modder River (below MRS 3)

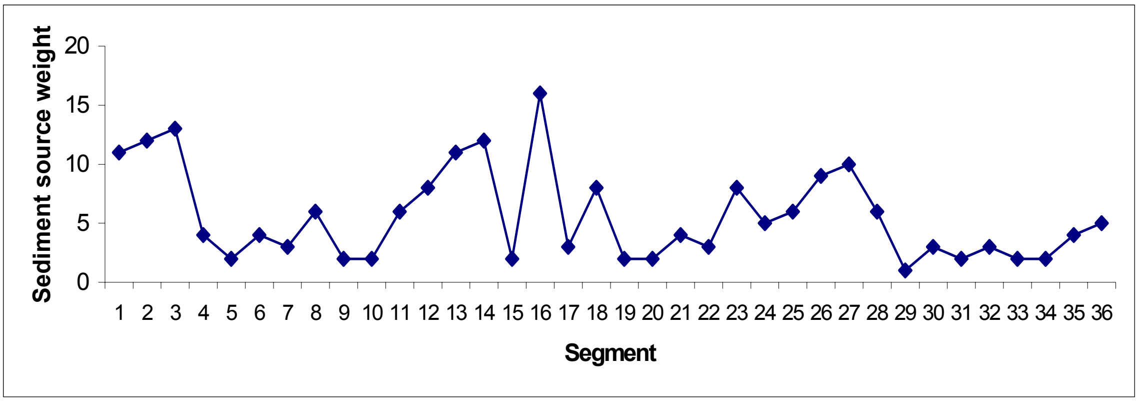


Figure 5.6: Spatial variation of bank erosion along the Modder River

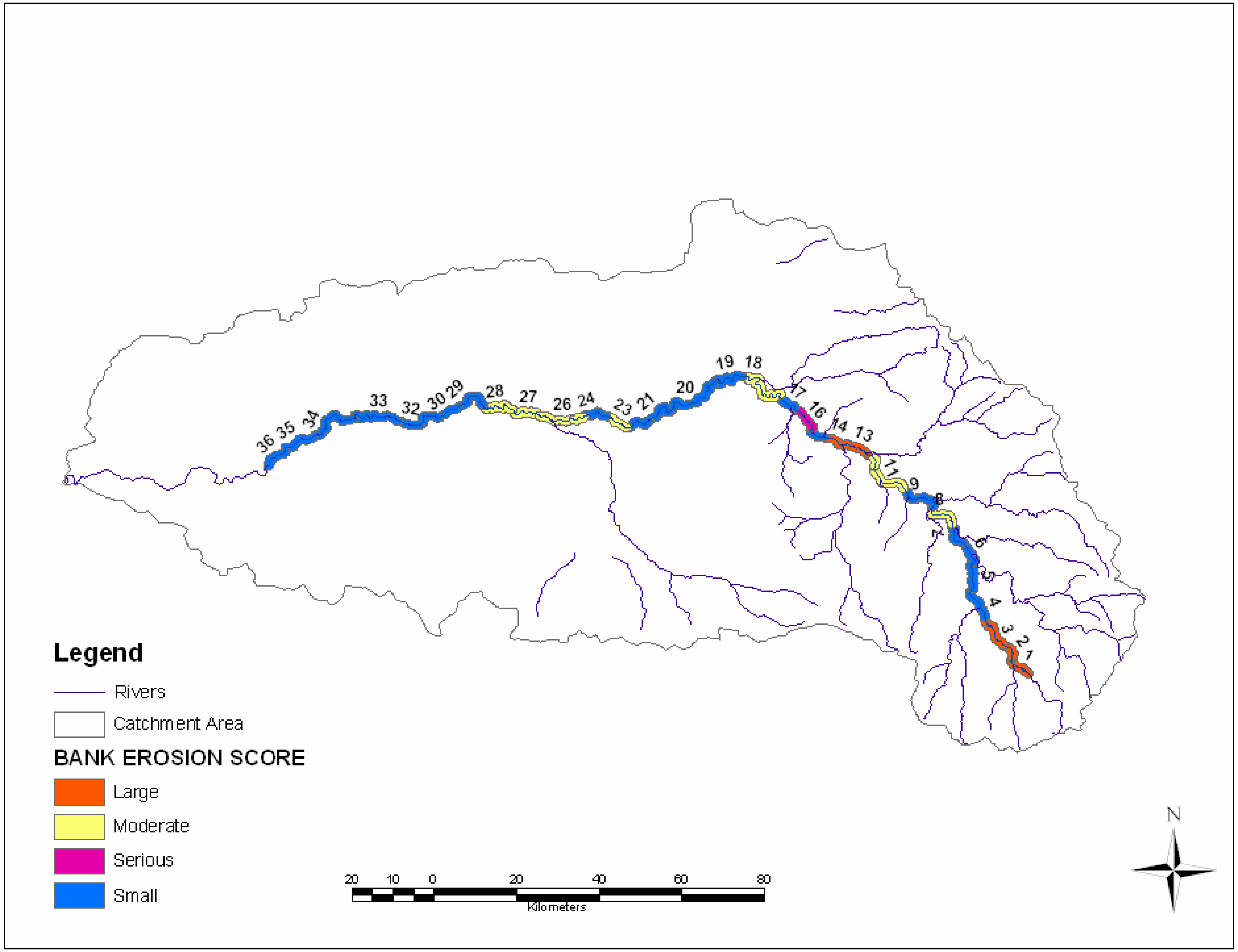


Figure 5.7: Bank erosion scores for every 5km segment

5.4.1 Riparian gully erosion

Figures 5.8 and 5.9 show the spatial variation of gully erosion on the banks of the Modder River, forming a buffer up to 5 m from the main stream. The two figures show that in segments 5, 6, 7 and 8, immediately below the Rustfontein Dam, there is an extremely high rate of gully erosion. The density of gullies in these segments is very high at about 50m from the main stream. However some recovery is taking place since these segments are now colonised by high vegetation cover (refer to Figure 5.4). Bushes and trees are now growing in these segments. Vegetation distribution in gullies is also important for reducing sediment yield at their outlets. Low vegetation in the gully floor traps sediments and thus plays a significant role in reducing erosion.

Segments 26 and 27 show a high rate of gully erosion, classified as ***very critical*** in Figure 5.9. Segment 18 is classified as ***serious***.

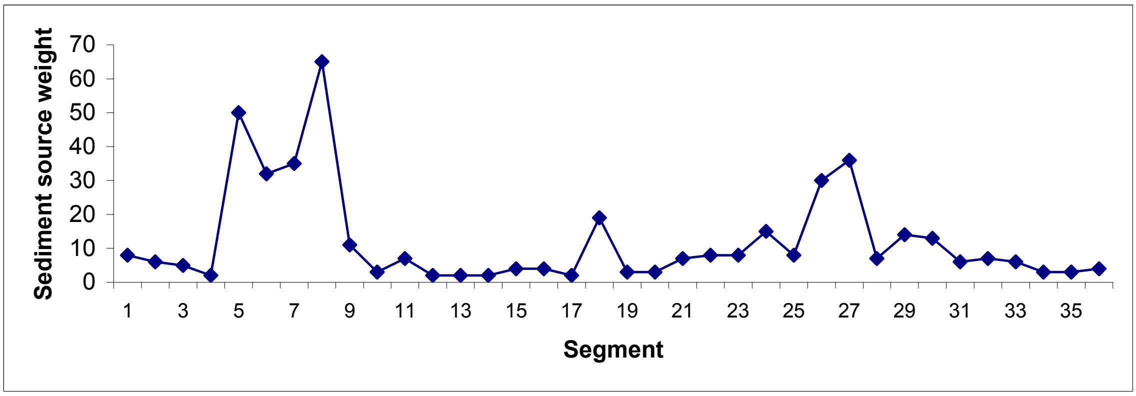


Figure 5.8: Spatial variation of riparian gully erosion along the Modder River

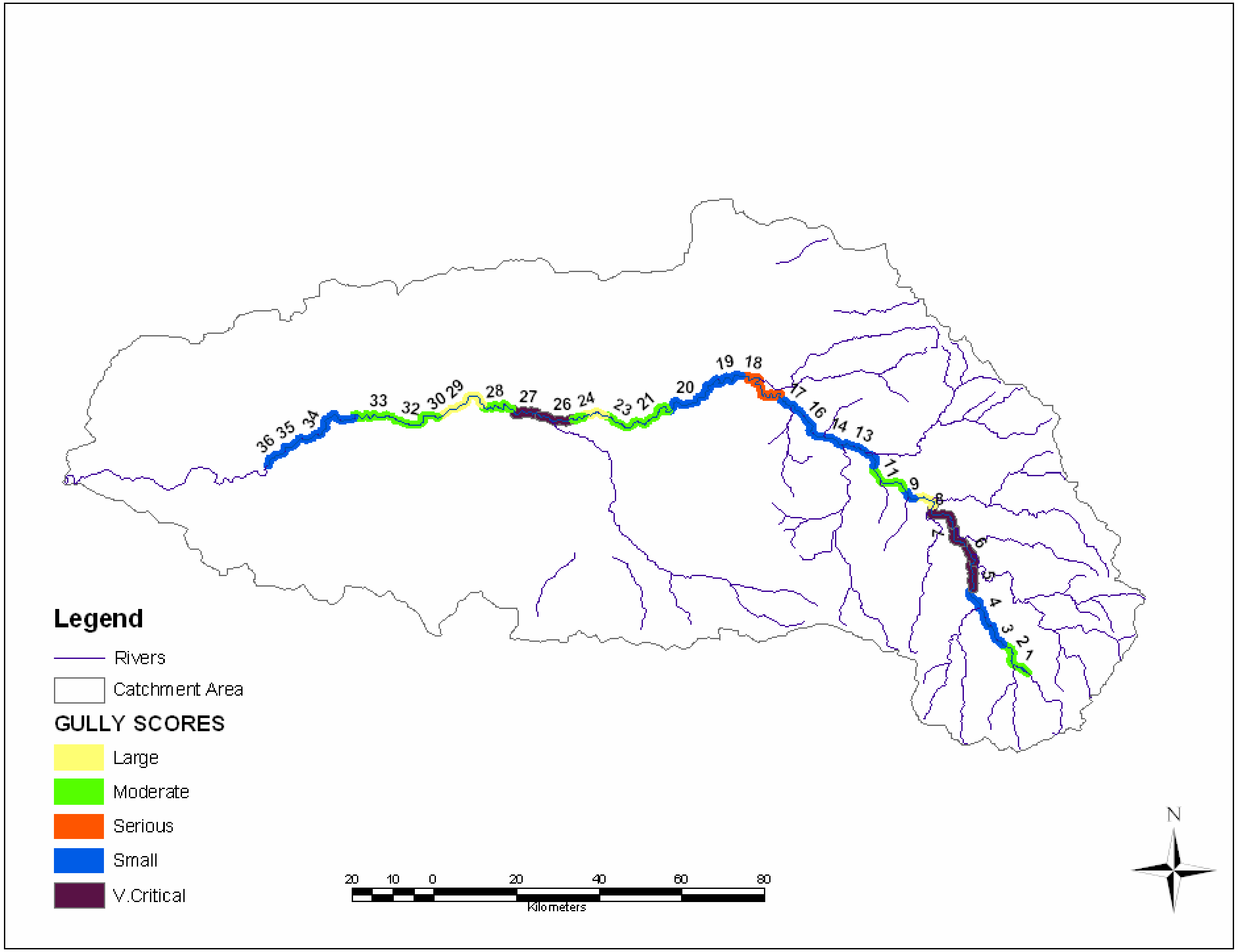


Figure 5.9: Bank gully scores for every 5km segment

5.5 IMPOUNDMENTS

The Modder River has a very high concentration of weirs/dams (Figure 5.10). According to Seaman *et al.* (2001), there is a weir across every dyke along the Modder River. The Modder River plays an important role in the water supply to domestic, agricultural and industrial use in the Bloemfontein, Botshabelo and Thaba N'chu areas.

According to the 2001 report on the state of the Modder River, the morphology of the Modder River has been significantly influenced by artificial structures such as reservoirs, as they considerably affect the fluvial systems by reducing the magnitude and frequency of the runoff, increasing evaporation, restricting sediment transport (Plate 5.7) and increasing scour downstream (Plate 5.8).

Fieldtrip, July 2003

Plate 5.7: Sediment transport restricted by a structure

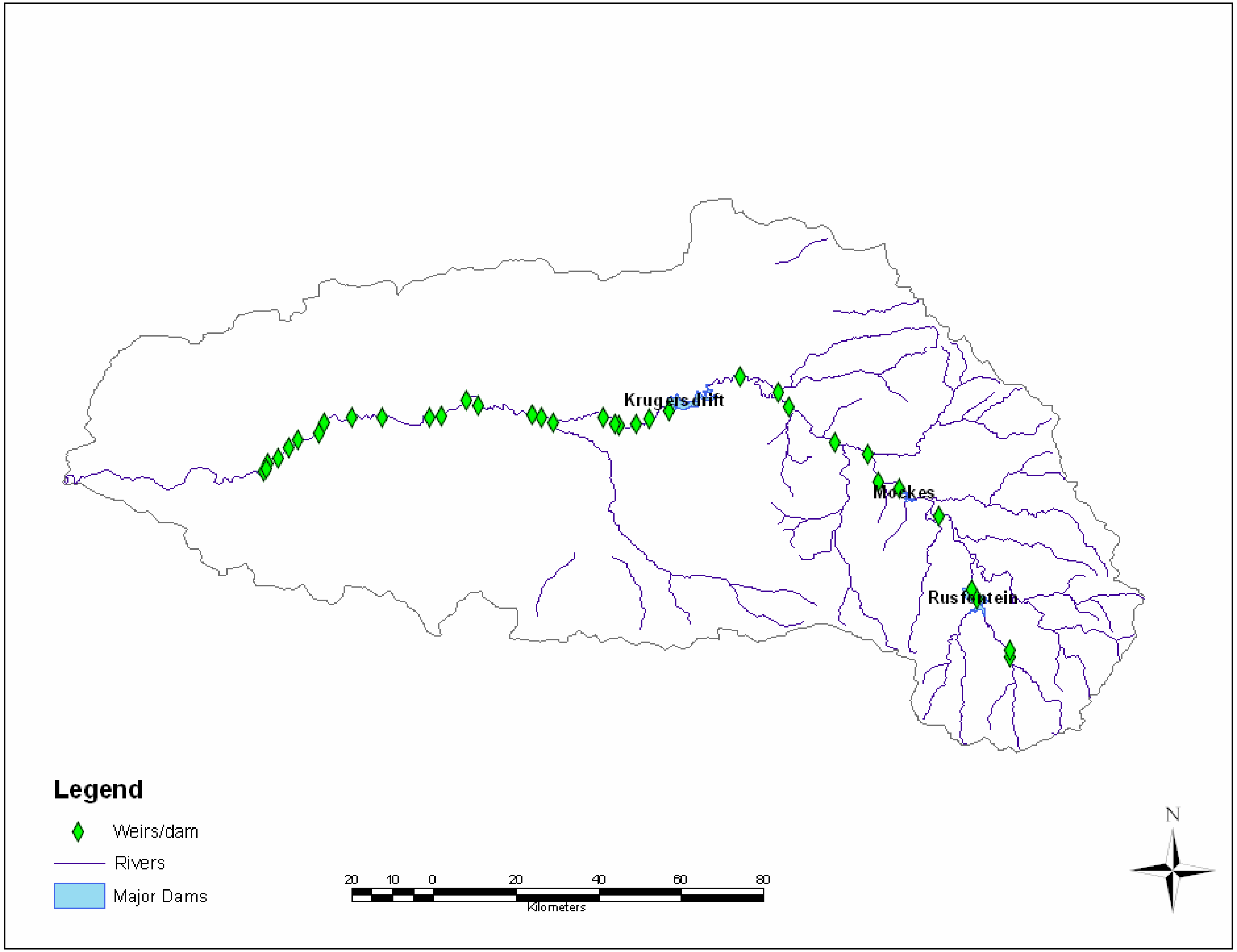


Figure 5.10: Impoundments along the 5km segments

Fieldtrip, July 2003

Plate 5.8: Significant changes to the channel below a weir and bridge (MR 3) prevented by lack of sediment inputs

5.6 THE CHANNEL FORM OF THE MODDER RIVER

Figure 5.11 shows ten sites where the cross-sections of the Modder River were measured by using an A-frame and clinometer. Considering the variations of the bankfull widths and bankfull depths along the Modder River in the downstream direction in Figures 5.12 and 5.13, the graphs show an overall increase in the channel dimensions as the drainage area increases from reach MR1 to reaches MR6 and MRS11(Figure 5.14). The channel dimensions then decrease further downstream as the river flows over a very flat terrain and they increase in dimension near the confluence at reach MR9. Only the part of the Modder River above the Krugersdrift Dam, from MR1 to MR6 (Soetdoring), complies with the theoretical river model.

Below the Krugersdrift Dam, channel dimensions decrease; this could be because the river flows through an area of very low gradient where numerous pans appear. These pans are filled after rainfall in the summer months but they hardly ever overflow, therefore contributing very little to the runoff (2,5mm) into the Modder River (Midgley *et al*, 1994a). Here too, the Krugersdrift Dam has two immediate effects on

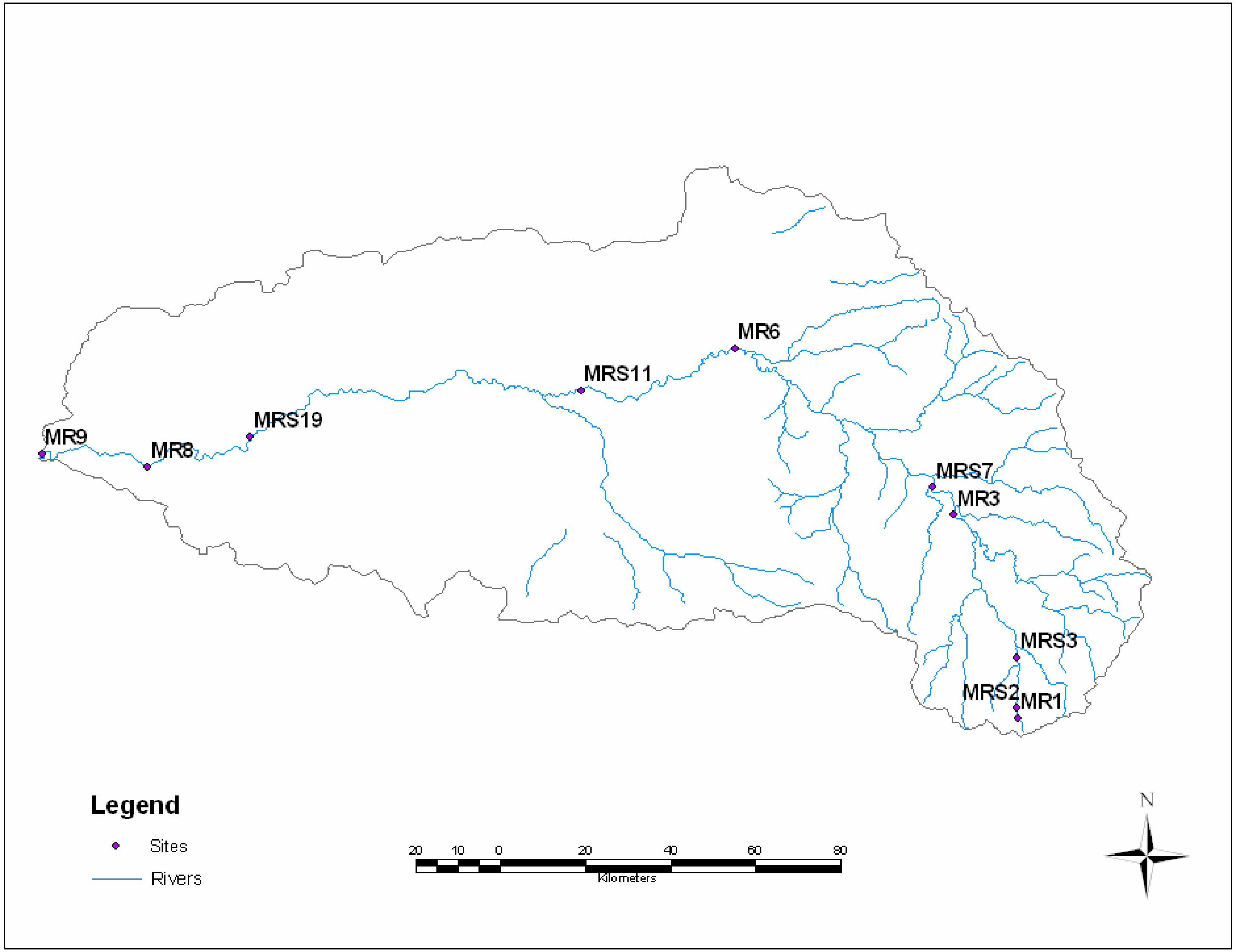


Figure 5.11: Ten sites where the channel form characteristics along the Modder River were measured

the Modder River: restricting sediment transport and increasing scour downstream of the dam.

Table 5.1: Characteristics of the form of the Modder River

Sites	W : D ratio	Catchment area (ha)	Bankfull Depth (m)	Bankfull Width (m)
MR1	13.66	917.00	1.94	26.50
MRS2	6.96	4 273.00	2.37	16.49
MRS3	20,89	17 700,00	2.41	50,34
MR4	14.89	163 486.00	2.75	40,95
MRS7	13.53	224 930,50	3.89	52.63
MR6	21.38	553 661.25	4.70	100,49
MRS11	6.51	605 924.75	6.74	43.91
MRS19	9.76	751 969.00	3.09	30,15
MR8	7.87	790 720,25	2.82	22.18
MR9	6.37	832 543.75	6.96	44.34

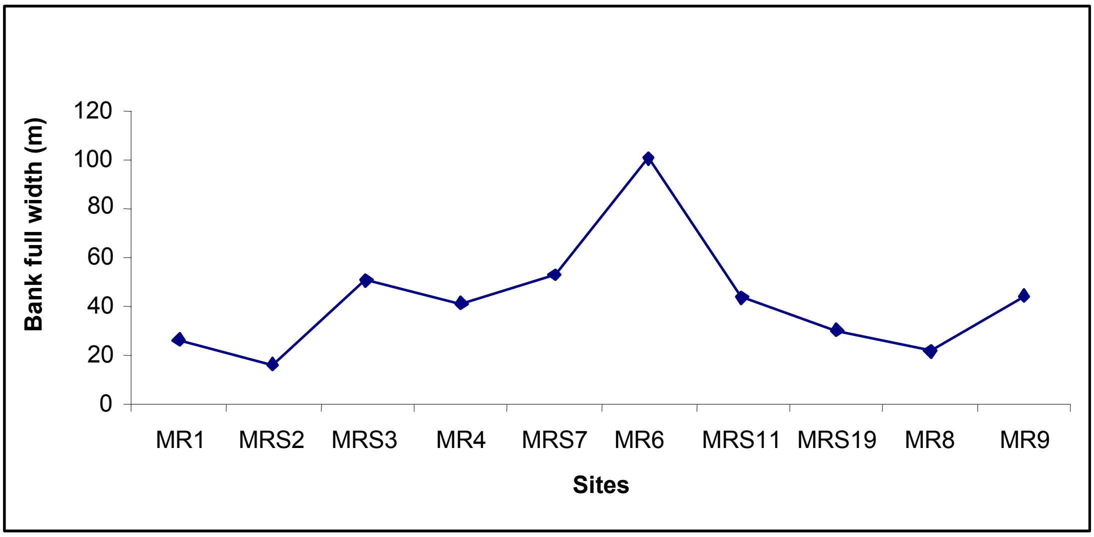


Figure 5.12: Bankfull width on ten sites along the Modder River

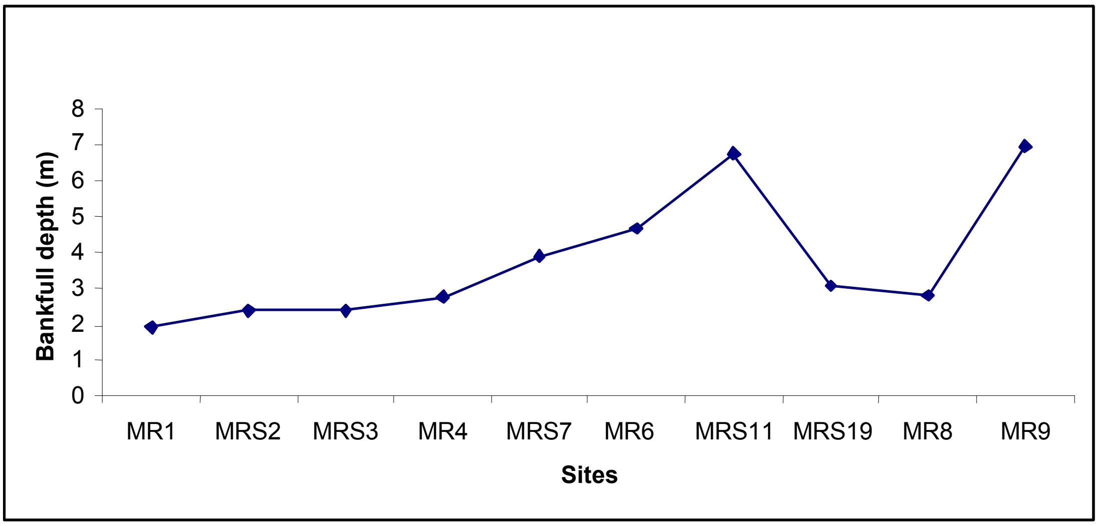


Figure 5.13: Bankfull depth on ten sites along the Modder River

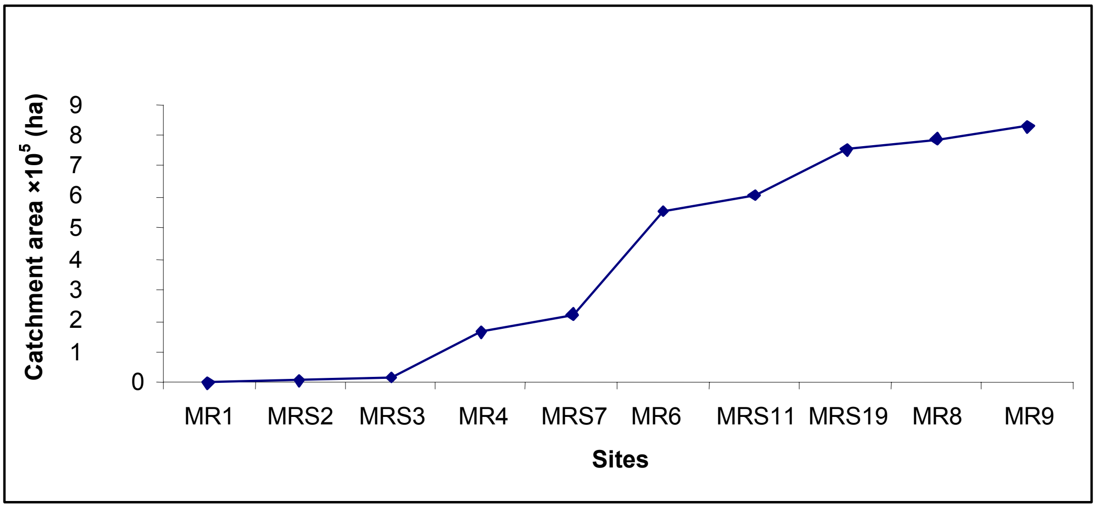


Figure 5.14: Catchment area on ten sites along the Modder River

5.7 SUMMARY

The silt/clay content in the banks of the Modder River is quite low. Most of the segments are covered with grass, bushes and trees showing high vegetation density on the banks. Bank erosion is not very active owing to the riparian vegetation. Serious bank gully erosion is taking place downstream of the Rustfontein Dam and at the confluence of the Kaalspruit and the Modder River. The Modder River has a very large number of dams. Channel dimensions show a decrease at some point along the Modder River.

CHAPTER 6
DISCUSSION & CONCLUSION

6.1 INTRODUCTION

In this chapter sediments within the main course of the Modder River are discussed, focusing on how sediments are transported through the course of the channel. The major possible sediment sources and stability of the banks of the Modder River are evaluated. The main point of interest is the hypothesis that the high sediment load in the Modder River main course is caused more by the riverbank processes than by the surface of the basin (Barker, 2002:186). The conclusions are made based on the findings of the study**.** Finally, recommendations on future studies are proposed.

6.2 SEDIMENT TRANSFER

6.2.1 Channel form and bank-forming material

It is generally assumed that the channel functions as a system and that sediment is moved through that system. But the sediments in the Modder River are not moved throughout the system due to the effects of dams.

Schumm (1977:110) postulated, “The percentage of silt/clay in the banks of a channel reflects the nature of sediment moving through that channel. The type of sediment load is considered to be a more important control on stable channel shapes than the total quantity of sediment transported through the channel.” The material analysed from the banks of the Modder River reflects that material transported is mostly fine sand (0,106mm) (Appendix B). The average silt/clay content in the twenty-one sites sampled is 30%, which implies that the channel shape of the Modder River is mostly wide and shallow, and indicates great width : depth ratios throughout the channel. But the trend of width : depth ratios along the Modder River in Figure 6.1 below show that the upstream sites have greater width : depth ratios (greater than 10) than the downstream sites.

The channel shape (width and depth) is systematically related to bankfull discharge. Channel shape adjusts to accommodate the downstream changes of stream discharge and sediment load supplied by the drainage basin, within constraints imposed by boundary composition, bank vegetation and valley slope (Knighton, 1998). In a natural (unmodified) fluvial system, discharge increases in the downstream direction as more water is added through rainfall, tributary streams and groundwater seeping into the stream. The reduced channel cross-sections of the Modder River indicate reduced sediment load within the system.

According to a number of authors who studied the nature of rivers, such as Schumm, 1977; Chorley *et al.* 1984; Summerfield, 1991 and others) natural channels with a width : depth ratio of less than 10 are narrow and deep, adjusted for transporting suspended load material and natural channels with width : depth ranging from 10 – 40 for transporting mixed load material. The Modder River is capable of transporting mixed loads above site MR6 (upstream of Krugersdrift Dam) and transports suspended load material downstream. The analysis of the channel form of the Modder River indicates that the effects of impoundments, reducing the sediment load, have modified its form.

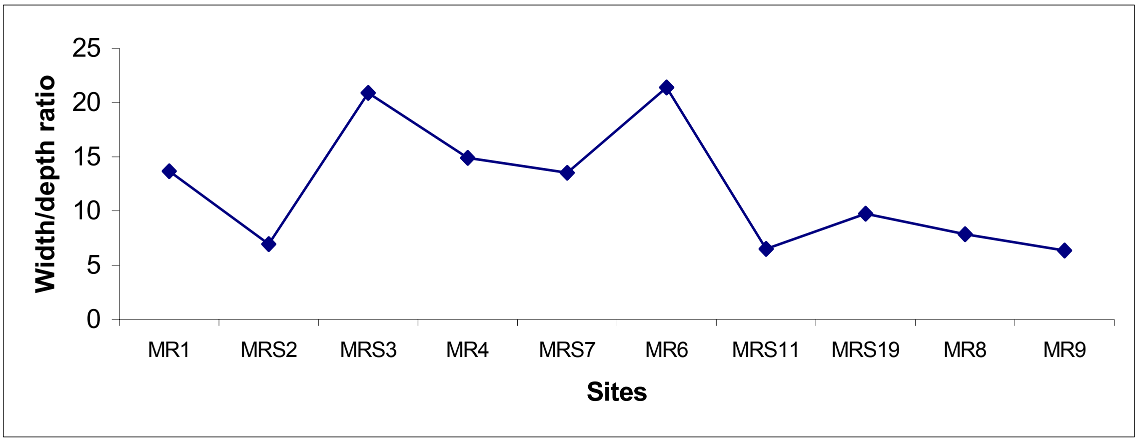


Figure 6.1: Width : depth ratio on ten sites along the Modder River

6.2.2 Impoundments

The number of dams/weirs along the Modder River is highly concentrated. Approximately every 5km there is a weir (Figure 5.10). Hence the Modder River has a very high likelihood of lacking coarse sediment load owing to its high concentration of dams/weirs trapping sediments behind their walls.

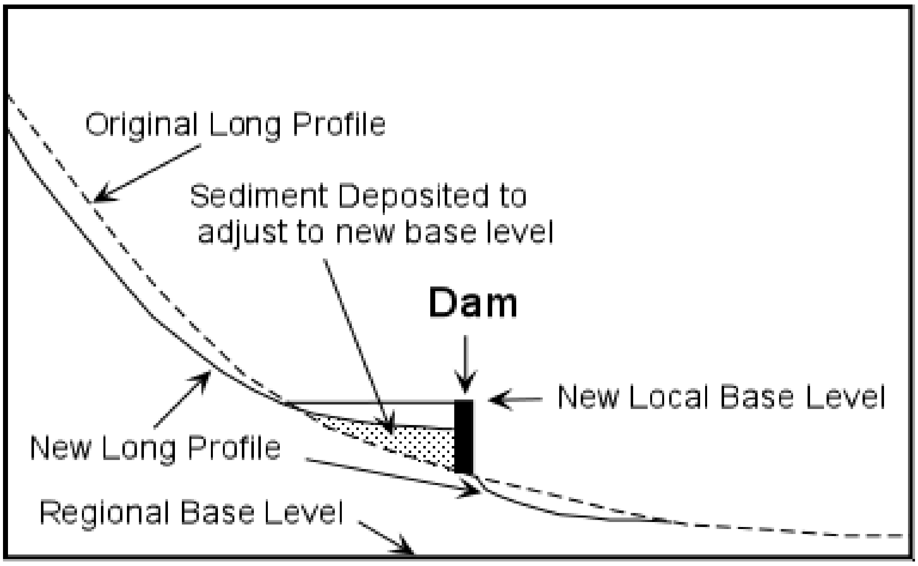
Verstraeten and Poesen (2000:220) state:

> “It is the nature of rivers that they transport sediment, and it is the nature of reservoirs that they should reduce the velocity of flow from that of the natural river and so encourage sediment deposition.”

Immediately upstream from a dam, the velocity of the stream is lowered so that deposition of sediment occurs, depending on the nature of the particles within the sediment load. The sediment load is transported in two modes: in suspended and in bed-sediment loads. The bed-sediment load is the part of the total load that travels immediately above the bed and is supported by inter-granular collisions rather than fluid turbulence. On the other hand, the suspended sediment load is primarily supported by fluid turbulence. Thus, bed-sediment load mainly includes the coarse materials that are transported by saltation. This means that most of the coarse material will be deposited behind the dam wall since the flow velocity will be reduced and the channel flow becomes incompetent to transport coarse material.

The velocity at which a particle settles on a channel bed is known as its fall velocity. It is the function of its density, size and shape and of the viscosity and density of the transporting material. As flow velocity decreases, the coarser sediment begins to be deposited while the finer particles remain in motion or suspense. Suspended load is invariably of the fine calibre and includes all particles prevented from settling by the upward momentum imparted by eddies within turbulent flows. The finest fraction of suspended load is the wash load, consisting of very small clay-sized particles that are in permanent suspension as long as some flow is maintained.

When a dam (natural or artificial) impedes stream flow, the stream adjusts to the new base level by adjusting its long profile, causing the gradient to decrease.



Source: Nelson, 2003

Figure 6.2: A long profile of a river affected by a dam

In Figure 6.2, the long profile above and below the dam are adjusted from the original profile due to artificial structure. Erosion takes place downstream from the dam (especially if it is a natural dam or road crossing and water can flow over the top).

Impoundments, regardless of their size or function, capture stream flow from rivers of different magnitudes. Together with the stream-flow, sediment load will enter the reservoir or pond, depositing part of it, depending on the trap efficiency of the impoundment. Chakela (1981:47) and Verstraeten and Poesen (2000:222) define the trap efficiency of the impoundment as the ratio of the quantity of sediment deposited in the impoundment to the total inflow into the impoundment. Trap efficiency is also very important in sediment yield studies.

As the sediments flow into successive dams/weirs in the Modder River main course, more and more sediments (depending on their size) settle into the dams resulting in a lack of sediments downstream, the river bed and banks being the only source of sediments.

6.3 SEDIMENT SOURCES

6.3.1 Modder River drainage and the Novo Transfer Scheme

Tributary sediment input is one of the potentially destabilising phenomena in increasing sediment supply on the Modder River by influencing how much and what type of sediment is stored and transported through the channel network. The Modder River catchment area reveals a well-developed dendritic drainage pattern on the eastern part whereas the western part is dominated by pans - indicating an endoreic drainage pattern (Barker, 2002). According to Midgley *et al*. (1994a), most of the natural runoff (50mm) into the Modder River is from above the confluence of the Modder and the Klein Modder Rivers. The rest of the Modder River catchment is relatively flat and very little runoff (2,5mm) occurs. Segments 1, 2, 3, 4, 5 and 6 appearing above this confluence have a higher potential of sediment delivery, owing to higher natural runoff, than in the rest of the segments.

The other possible high sediment source in the upper reaches of the Modder River is the Caledon-Modder (Novo) Transfer Scheme that pumps untreated water from the Caledon River into Knellpoort Dam, then into the Modder River, upstream of the Rustfontein Dam. The transfer scheme has increased the flow of the Modder River in the upper reaches. This implies that the eroding power of the channel has increased; the river now has a higher capability of eroding on its bed and banks. Plates 6.1 and 6.2 show the flow in the Modder River, before and during the Novo Transfer Scheme. The active channel width has increased. Plate 6.2 shows high turbulence on this site, implying an increased flow velocity.

Fieldtrip, July 2003

Plate 6.1: Site MRS 3 before the Novo Transfer Scheme

Fieldtrip, March 2005

Plate 6.2: Sites MRS 3 during the Novo Transfer Scheme

6.3.2 Sediment source weights

The net sediment source weights of the 5km segments of the Modder River are shown in Figure 6.3 below. The segments that show high net sediment source weight around 40 are those that have tributary sediment input (segments 1, 4, 5, 6, 7, 8, 18, 26 and 27) and high gully sediment source weights (Figure 5.7).

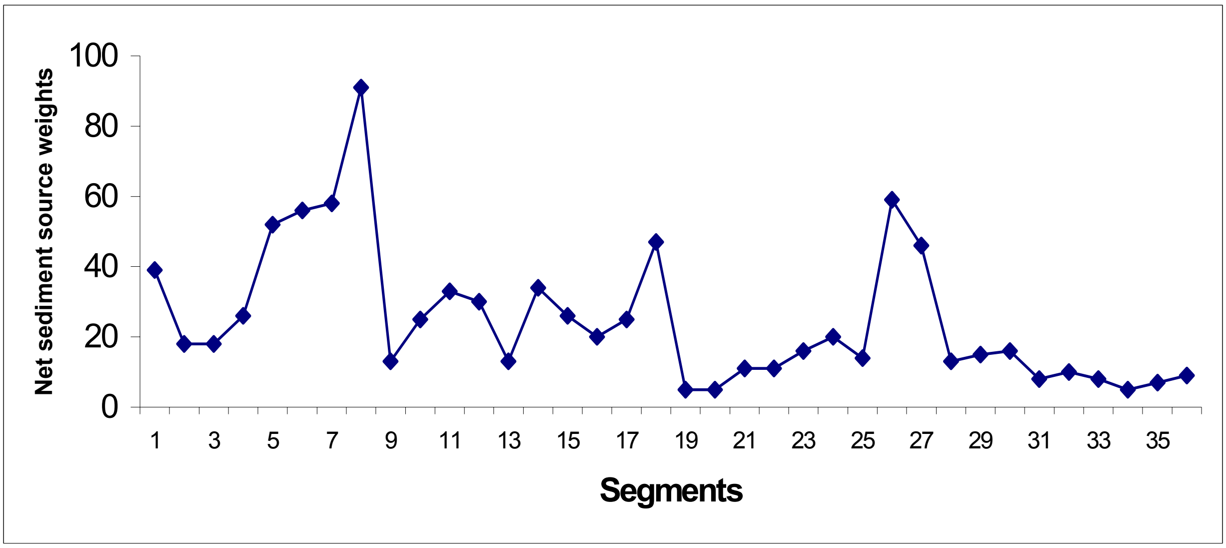


Figure 6.3: Net sediment source weights for the segments

The segments in which bank gully erosion is classified as very critical and serious are segments 5, 6, 7, 8, 18, 26 and 27, implying high-localised erosion in the segments. These segments supply considerable amounts of sediments into the Modder River in the wet seasons since they aggravate off-site effects of water erosion. Bank gullies retreat by head cut migration into the more gentle sloping soil surface of the bank shoulder and farther into low-angled pediments and agricultural land. The bank gully outlets on the river banks show some recovery from erosion by colonising trees, bushes and some grasses. Vegetation on the gully outlets traps sediments but the gully heads remain bare. The area in these segments being much degraded could lead to severe management problems.

The banks of the Modder River have low silt/clay content (average 30%) (Appendix B), classified as non-cohesive material banks. The low percentage of silt/clay content in the banks of the Modder River makes them very susceptible to fluvial erosion, particularly where the banks are steepened. These banks can possibly be the major sediment source into the mainstream channel. However, aerial observations of bank erosion show low sediment source weight which could be due to the banks of the Modder River being colonised by trees and bushes (Figure 5.5) that reinforce the non-cohesive banks. Well-vegetated banks are cited as being some 20 000 times more resistant to erosion than similar bank sediment without vegetation (Stott, 1997:395; Abemethy and Rutherfurd, 1998:56; Simpson and Smith, 2001:339). The banks of the Modder River are protected against mass failure by trees and bushes that increase the bank-substrate strength in most the segments. Abemethy and Rutherfurd (2000:921) state, “Vegetated banks in flood-plain reaches can maintain higher and steeper geometries than their vegetation-degraded counterparts.” In sections of the river, downstream of the weirs and dams, the common reed is encroaching on the channel owing to a lack of strong current to remove the reed rhizomes, thus reducing the rate of flow and promoting the deposition of sediments (Plate 6.3).

Fieldtrip, March 2005

Plate 6.3: Channel encroached by reeds (downstream of Rustfontein Dam)

6.4 BANK STABILITY

The banks of the Modder River show the luxuriant growth of vegetation. Trees can reduce erosion through mechanical strengthening and binding of the banks by roots. Vegetation protects banks by creating a lower velocity buffer between the soil in the banks and the erosional forces of the main current. The roots of trees and bushes are an important component of the Modder River banks for increasing the bank resistance to erosion and the management of channel width (Plate 6.4). Woody debris in the Modder River acts as a hydraulic roughness element that removes momentum from the flow and reduces the capacity of the channel to transport sediment.

Fieldtrip, March 2005

Plate 6.4: Vegetation stabilising the banks of the Modder River (Perdeburg: MRS 19)

6.5 CONCLUSIONS

The channel form of the Modder River indicates a decrease in sediment loads since the channel form shows some shrinkage immediately below the Krugersdrift Dam. The Modder River transports progressively fewer sediments downstream owing to the high number of constructed dams for the supply of water for industrial, irrigation and domestic use. The majority of reaches along the Modder River are deprived of sediment loads because of the presence of these dams and because of the lack of channel gradient for the main part of the catchment area. The local gradient is nowhere more than about one degree (Barker, 2002).

In considering the drainage pattern of the Modder River catchment area that reveals well-developed dendritic drainage in the eastern part and endoreic drainage in the western part, it may be assumed that tributaries in the eastern part of the catchment are major sediment sources in the Modder River. This raises the question of what the sediment sources in the western part of the catchment are. The banks of the Modder River are possible sediment sources in this part of the catchment, but the observations of the characteristics of the banks of the Modder River reveal that they are resistant to erosion because of the luxuriant vegetation growth and low stream power and because of the channel gradient.

Another question arises on whether the Modder River really has as high sediment loads as its name suggests. Given the current state of the Modder River, high sediments in the river are highly localised at certain sections of the stream. The segments showing a high contribution of sediments into the Modder River are 5, 6, 7, 8, 18, 26 and 27, which are much degraded owing to the high density of bank gullies. Suspended sediment loads are the major sediments in the Modder River. Sediment transfer depends on the availability of sediment sources (Liébault, Clément, Piégay, Rogers, Kondolf, and Landon, 2002: 64). The coarse sediments appearing in the Modder River are derived from the riverbanks.

The channel dimensions of the Modder River reflect the magnitude of the water and sediment discharges, but in the absence of hydrologic and stream flow records, an understanding of stream morphology helps delineate environmental changes. In the Modder River the construction of successive dams has reduced high sediment loads. The possible reason for the low percentage of silt/clay in the banks of the Modder River is that approximately ninety percent of the river can be categorised as belonging to the lowland sand bed or lowland plain zone (Seaman *et al.,* 2001).

The hypothesis that the high sediment load in the Modder River main course is caused more by the riverbank processes than by the surface of the basin (Barker, 2002:186) is therefore rejected because the banks of the Modder River are stabilised by the luxuriant growth of vegetation.

6.6 RECOMMENDATIONS

The lack of long-term data series on the Modder River and in most of the southern African geomorphological literature is a serious limitation (Beckedahl, Sumner and Garland, 2002:148). Because of the general lack of reliable data that can be used to validate mathematical process-response models for the region, it may lead to data from often vastly disparate studies to be cobbled together in an attempt to extend the length of data trends.

More geomorphological studies need to be conducted on the Modder River since its ‘high’ sediment loads are contributed neither by the surface of the basin, nor the river banks. Future studies could investigate whether the ‘mud river’ is really muddy. Stream flow records of the Modder River can determine its authentic amount of sediment loads. The trap efficiencies of the reservoirs in the Modder River catchment could also be very significant in the studies of sediment yield.

The riparian vegetation on the banks of the Modder River needs to be managed in most of the segments (5, 7, 10, 11, 12, 13, 18, 22, 23, 25, 26, 28, 31, 34 and 36). The encroachment of trees into the stream causes channel narrowing by encouraging deposition and increasing the channel roughness. The presence of overhanging and dead trees, known as large woody debris, in the channel may lead to partial blockage of the stream and the jamming of the channel, especially in weirs during very high flows.

BIBLIOGRAPHY

Abam, TKS & Omuso, WO. 2000, ***Technical note on river cross-sectional change on the Niger Delta***. *Geomorphology*, 34(1- 2): 111 - 126.

Abemethey, B & Rutherfurd, ID. 1998. ***Where along a river's length will vegetation most effectively stabilize stream banks?*** *Geomorphology*, 23(1): 55 – 75.

Abemethey, B & Rutherfurd, ID. 2000. ***The effect of riparian tree roots on the mass-stability of riverbanks***. *Earth Surface Processes and Landforms*, 25: 921 – 937.

Barker, CH. 2002. **A morphometrical investigation into landscape development in the Central Free State** (Translated title). Unpublished PhD Thesis. Bloemfontein: University of the Free State.

Beckedahl, HR; Sumner, PD. & Garland, G. 2002. **South African Geomorphology: Critical Choices For The Future.** *South African Geographical Journal,* 84(1): 145-152.

Brierley, G; Fryirs, K; Outhet, D & Massey, C. 2002. ***Application of the River Styles framework as a basis for river management in New South Wales, Australia***. *Applied Geography,* 22: 91 – 122.

Brierley, GJ & Murn, CP. 1997. ***Europe, impacts on downstream sediment transfers and bank erosion in the Cobargo catchment, New South Wales, Australia***. *Catena,* 31: 119 – 136.

Brookes, A. 1995. ***Challenges and objectives for geomorphology in U.K. River Management***. *Earth Surface Processes and Landforms*, 20: 593 – 610,

Camenen, B & Larson, M. 2005. ***A general formula for non-cohesive bed load sediment transport***. *Estuarine, Coastal and Shelf Science*, 63:249 – 260,

Chakela, QK. 1981. ***Soil Erosion and Reservoir Sedimentation in Lesotho***. Department of Physical Geography, Uppsala University. UNGI Rapport No. 54 and Scandinavian Institute of African Studies, Uppsala 1981. 150 pp. ISBN 91-7106-186-X.

Chorley, RJ; Schumm, SA & Sugden, DE. 1984. **Geomorphology**. Singapore: Typeset.

Collins, AL & Walling, DE. 2004. ***Documenting catchment suspended sediment sources: problems, approaches and prospects***. *Progress in Physical Geography*, 28(2): 159 – 196.

Coroza, O; Evans, D & Bishop, I. 1997. ***Enhancing runoff modeling with GIS***. *Landscape and Urban Planning*, 38: 13 – 23.

Cooper, P. 2003. ***Effects of silt-clay content on the susceptibility of riverbanks to sub-aerial erosion***. *Geomorphology*, 56 (1 – 2): 95 – 108.

Dapporto, S; Rinaldi, M & Casagli, N. 2001. ***Failure mechanisms and pore water pressure conditions: analysis of a riverbank along the Arno River (Central Italy)***. *Engineering Geology,* 61(4): 221 – 242.

Dardis, GF; Beckedahl, HR & Stone, AW. 1988. **Fluvial systems** in Moon, BP & Dardis, GF (Eds). **The Geomorphology of Southern Africa,** (pp. 30 – 56). Johannesburg: Southern.

DEAT (Department of Environment and Tourism). 1999. **Environmental Potential Atlas of South Africa**. Pretoria: DEAT.

DEAT (Department of Environment and Tourism). 2001. **Environmental Potential Atlas of South Africa**. Pretoria: DEAT.

Dollar, ESJ. 2000. ***Progress report: Fluvial geomorphology***. *Progress in Physical Geography*, 24(3): 385 – 406.

Dollar, ESJ. 2002. ***Progress report: Fluvial geomorphology***. *Progress in Physical Geography,* 26(1): 123 – 143.

Downs, PW & Simon, A. 2001. ***Fluvial geomorphological analysis of the recruitment of large woody debris in the Yalobusha River network, Central Mississippi, USA***. *Geomorphology*, 37: 65–91.

Duan, JG. 2001. ***Numerical analysis of river channel processes with bank erosion***. *Journal of Hydraulic Engineering*, 127(8): 702 – 703.

DWAF - Department of Water and Forestry. 1999. **Catchment Management Strategy for the Modder and Riet Rivers. Phase 1: Situation and Draft Management Strategy**.

Eaton, BC & Miller, RG. 2004. ***Optimal alluvial channel width under a bank stability constraint***. *Geomorphology*, 62(1 – 2): 35 – 45.

Finlayson, DP & Montgomery, DR. 2003. ***Modelling large-scale fluvial erosion in geographic information systems***. *Geomorphology*, 53(1 – 2): 147 – 164.

Friedman, JM; Osterkamp, WR & Lewis, WM. 1996. ***The role of vegetation and bed-level fluctuations in the process of channel narrowing***. *Geomorphology*, 14: 341-351.

Gilvear, DJ. 1999. ***Fluvial geomorphology and river engineering: future roles utilizing a fluvial hydro–systems framework***. *Geomorphology*, 31(1–4): 229 – 245.

Goodson, JM; Gurnell, AM; Angold, PG & Morrissey, IP. 2002. ***Riparian seed banks along the lower River Dove, UK: their structure and ecological implications***. *Geomorphology*, 47(1 – 2): 45 – 60,

Goudie, A. 1990. **Geomorphological Techniques** (2nd ed.). London: Oxford.

Haschenburger, JK & Rice, SP. 2004. ***Changes in woody debris and bed material texture in a gravel-bed channel***. *Geomorphology*, 60 (3 -4): 241–267.

Heritage, GL; Van Niekerk, AW; Moon, BP; Broadhurst, LJ; Rogers, KH & James, CS. 1997. ***The geomorphological response to changing flow regimes of the Sabie and Letaba River systems***. Water Research Commission Report No 376/1/97. Water Research Commission, Pretoria, South Africa.

Hey, RD. 1997. **Stable river morphology** in Thorne, CR, Hey, RD & Newson, MD (Eds). **Applied Fluvial Geomorphology for River Engineering and Management** (pp. 223 – 236). Chichester: Wiley.

Hooke, JM. 1999. ***Decades of change: Contributions of geomorphology to fluvial and coastal engineering and management***, *Geomorphology*, 31(1–4): 373 – 389.

Hooke, JM. 2003. ***Coarse sediment connectivity in river channel systems: a conceptual framework and methodology***. *Geomorphology*, 56(1-2): 79–94.

Hughes, AO & Prosser, IP. 2003. **Gully and Riverbank Erosion Mapping For The Murray-Darling Basin**. CSIRO Land and Water, Canberra Technical Report 3/03.

James, A. 1999. ***Time and the persistence of alluvium: River engineering, fluvial geomorphology, and mining sediment in California***. *Geomorphology,* 31(1– 4): 265 – 290,

Kleynhans, CJ. 1996. ***A qualitative procedure for the assessment of the habitat status of the Luvuvhu River (Limpopo system, South Africa)***. *Journal of Aquatic Ecosystem Health*, 5: 41 – 54.

Knighton, D. 1987. **River channel adjustment, downstream dimensions** in Richards, K (Ed). **River Channels, Environment and Process**. Oxford: Blackwell.

Knighton, D. 1998. **Fluvial Forms and Processes, a new perspective**. London: Arnold.

Kondolf, GM; Piégay, H & Landon, N. 2002. ***Channel response to increased and decreased bed-load supply from land use change: Contrasts between two catchments***. *Geomorphology*, 45(1–2): 35 – 51.

Lawler, DM; Thorne, CR & Hooke, JM. 1997. **Bank erosion and instability** in Thorne, CR, Hey, RD & Newson, MD (Eds). **Applied Fluvial Geomorphology for River Engineering and Management** (pp. 137 – 172). Chichester: Wiley.

Liébault, F; Clément, P; Piégay, H; Rogers, CH; Kondolf, GM. &Landon, N. 2002**. Contemporary channel changes in the Eygues basin, southern French Prealps: the relationship of subbasin variability to watershed characteristics.** *Geomorphology*, 45: 53 – 66.

Macklin, MG & Lewin, J. 1997. **Channel, floodplain and drainage basin response to environmental change** in Thorne, CR, Hey, RD & Newson, MD (Eds). **Applied Fluvial Geomorphology for River Engineering and Management** (pp. 15 – 45). Chichester: Wiley.

Midgley, DC; Pitman, WV & Middleton, BJ. 1994a. **Surface Water Resources of South Africa***.* Vol. 2, Drainage C, Vaal. Appendices. WRC report no. 298/2.1/94. Pretoria: Water Research Commission.

Midgley, DC; Pitman, WV & Middleton, BJ. 1994b. **Surface Water Resources of South Africa, Books** of Maps, Vol. 2. WRC report no. 298/2.2/94. Pretoria: Water Research Commission.

Miller, RG & Quick, MC. 1998. ***Stable width and depth of gravel–bed rivers with cohesive banks***. *Journal of Hydraulic Engineering*, 124(10): 1005 – 1013.

Mosley, P. & Jowett, I. 1999. ***River morphology and management in New Zealand***. *Progress in Physical Geography*, 23(4): 541 – 564.

Nagata, N; Hosoda, T & Muramoto, Y. 2000, ***Numerical analysis of river channel processes with bank erosion***. *Journal of Hydraulic Engineering*, 26(4): 243 – 252.

Nelson, AN. 2003. **Streams and Drainage Basins**.
URL: http//www.tulane.edu/~sanelson/geol111/streams.htm

Newson, MD; Hey, RD; Bathurst, JC; Brookes, A; Carling, PA; Petts, GE & Sear, DA. 1997. **Case studies in the application of geomorphology to river management** in Thorne, CR, Hey, RD and Newson, MD (Eds.). **Applied Fluvial Geomorphology for River Engineering and Management** (pp. 311 – 364)*.* Chichester: Wiley.

Pizzuto, JE. 1984. ***Bank erodability of shallow sand-bed streams***. *Earth Surface Processes and Landforms*, 20: 113 – 124.

Poesen, J; Nachtergaele, J; Verstraeten, G & Valentin, C. 2003. Gully ***erosion and environmental change: importance and research needs***. *Catena,* 50: 91 – 133.

Raper, PE. 1987. **Dictionary of Southern African Place Names**. Johannesburg: Lowry Publishers.

Rey, F. 2003. ***Influence of vegetation distribution on sediment yield in forested marly gullies***. *Catena,* 50(2-4): 549 – 562.

Richards, KS & Lane, SN. 1997. **Prediction of morphological changes in unstable channels** in Thorne, CR, Hey, RD and Newson, MD (Eds.), **Applied Fluvial Geomorphology for River Engineering and Management** (pp. 269 – 292). Chichester: Wiley.

Rinaldi, M & Casagli, N. 1999. ***Stability of stream–banks formed in partially saturated soils and effects of pore water pressures: the Sieve River (Italy)***. *Geomorphology,* 26(4): 253 – 277.

RHP (River Health Programme). 2003. **State-Of-Rivers Report: Free State Region River Systems**. Department of Water Affairs and Forestry. Pretoria ISBN No: 0-62-31794-9.

Rovira, A; Batalla, RJ & Sala, M. 2005. ***Fluvial sediment budget of a Mediterranean river: the lower Tordera (Catalan Coastal Ranges, NE Spain)***. *Catena,* 60:19 – 42.

Rowntree, KM & Dollar, ESJ. 1996. ***Controls on channel form and channel change of the Bell River, Eastern Cape, South Africa***. *South African Geographical Journal*, 78(1): 20 – 28.

Rowntree, K & Wadeson, R. 1998. ***A geomorphological framework for the assessment of instream flow requirements***. *Aquatic Ecosystem Health and Management*, 1(2): 125 – 141.

Rowntree, KM & Wadeson, RA. 1999. **A hierarchical geomorphological model for the classification of selected South African rivers**. Water Research Commission Report No 497/1/99. Water Research Commission, Pretoria, South Africa.

Rowntree, KM & Ziervogel, G. 1999. **Development of an index of stream geomorphology for the assessment of river health**. National Aquatic Ecosystem Biomonitoring Programme Report Series No. 7. Pretoria, South Africa: Institute for Water Quality Studies, Department of Water Affairs and Forestry. RSA, 1999

Schumm, SA. 1977. **The Fluvial System**. New York: Wiley.

Seaman, MT; Roos, JC & Watson, M. 2001. ***The State of the Modder River,*** First Quarter 2001- a bio–monitoring report. Report to Bloem Water by the Centre for Environmental Management. Bloemfontein: University of the Free State, South Africa.

Sear, DA & Newson, MD. 2003. ***Environmental change in river channels: A neglected element towards geomorphological typologies, standards and monitoring***. *The Science of the Total Environment,* 310: 17 – 23.

Sear, DA; Newson, MD & Brookes, A. 1995. ***Sediment-related river maintenance: The role of fluvial geomorphology***. *Earth Surface Processes and Landforms*, *20*: 629 – 647.

Simon, A. 1995. ***Adjustment and recovery of unstable alluvial channels: Identification and approaches for engineering and management***. *Earth Surface Processes and Landforms,* 20: 611 – 628.

Simon, A & Downs, PW. 1995. ***An interdisciplinary approach to evaluation of potential instability in alluvial channels***. *Geomorphology*, 12(3): 215 – 232.

Simon, A; Curini, A; Darby, SE & Langendoen, EJ. 2000. ***Bank and near bank processes in an incised channel***. *Geomorphology,* 35(3– 4): 193 – 217.

Simpson, CJ & Smith, DG. 2001. ***The braided Milk River, northern Montana, fails the Leopold-Wolman discharge-gradient test***. *Geomorphology*, 41: 337 – 353.

Summerfield, MA. 1991. **Global Geomorphology: An Introduction to the study of landforms***.* New York: Wiley.

Stott, T. 1997. ***A comparison of stream bank erosion processes on forested and moor-land streams in the Balquhidder Catchments, Central Scotland***. *Earth Surface Processes and Landforms*, 22: 383 – 399.

Thorne, CR & Abt, SR. 1993. ***Analysis of riverbank instability due to toe scour and lateral erosion***. *Earth Surface Processes and Landforms*, 18: 835 – 843.

Thorne, CR & Tovey, NK. 1981. ***Stability of composite riverbanks***. *Earth Surface Processes and Landforms,* 6: 469 – 484.

Thorne, CR. 2002. ***Geomorphic analysis of large alluvial rivers***. *Geomorphology*, 44(3 – 4): 203 – 219.

Tsokeli, RD. 2003. **The channel form of the Modder River (Free State Province, South Africa)** (unpublished BSc Hons project). Bloemfontein: University of the Free State.

Vandekerckhove, L; Poesen, J; Wijdenes, DO & Gyssels, G. 2001. ***Short-term bank gully retreat rates in Mediterranean environments***. *Catena,* 44: 133 – 161.

Van Niekerk, AW & Heritage, GL. 1993. ***Geomorphology of the Sabie River: Overview and classification****.* Centre for Water in the Environment Report No: 2/93. Johannesburg: University of Witwatersrand.

Verstraeten, G. & Poesen, J. 2000. ***Estimating trap efficiency of small reservoirs and ponds: methods and implications for the assessment of sediment yield***. *Progress in Physical Geography*, 24(2): 219 – 251.

Wallerstein, NP & Thorne, CR. 2004. ***Influence of large woody debris on morphological evolution of incised, sand-bed channels***. *Geomorphology*, 57 (1-2): 53–73.

Watson, HK. 1990. **A comparative study of soil erosion in the Umfolozi Game Reserve and adjacent KwaZulu area from 1937 to 1983**. Unpublished PhD Thesis. Durban: University of Durban-Westville.

Western, AW; Finlayson, BL; McMahon, TA & O'Neill, IC. 1997. ***A method for characterizing longitudinal irregularity in river channels***. *Geomorphology*, 21: 39 – 51.

Winterbottom, SJ. 2000. ***Medium and short term channel planform changes on the Rivers Tay and Tummel, Scotland***. *Geomorphology*, 34(3 – 4): 195 – 208.

Zonge, KL; Swanson, S & Myers, T. 1996. ***Drought year changes in streambank profiles on incised streams in the Sierra Nevada Mountains***. *Geomorphology* 15(1): 47 – 56.

APPENDIX B: SEDIMENT SIZE DISTRIBUTION

Sediment Size	Size (mm)	MR1	MRS2	MRS3	MRS5	MRS20	MR3	MRS7	MRS21	MRS22	MRS23	MRS6	MRS11	MRS12	MRS13	MRS14	MRS15	MRS19	MRS17	MR8	MRS18	MR9	Average
Clay	0,002	16.00	20.00	16.00	26.00	18.00	26.00	14.00	16.00	38.00	28.00	22.00	12.00	16.00	22.00	18.00	14.00	14.00	16.00	24.00	18.00	24.00	19.90
Fine silt	0,02	4.00	2.00	4.00	2.00	2.00	2.00	2.00	4.00	4.00	2.00	2.00	1.00	1.00	1.00	2.00	1.00	1.00	4.00	1.00	2.00	2.00	2.19
Course silt	0,05	4.00	8.00	2.00	12.00	10.00	12.00	4.00	14.00	20.00	10.00	10.00	3.00	5.00	11.00	8.00	5.00	5.00	10.00	9.00	6.00	14.00	8.67
V fine sand	< 0,106	24.56	20,76	31.66	25.88	34.68	25.88	21.34	25.68	16.38	31.38	46.12	25.84	21.96	21.80	45.58	11.10	14.20	18.60	39.06	25.36	36.04	27.16
Fine sand	0,106	44.32	20,22	42.76	27.56	32.16	27.56	38.18	35.14	8.24	23.28	20,24	58.30	43.62	26.16	27.10	31.7	26.82	13.38	20,70	39.54	21.98	31.54
Medium sand	0,25	4.52	6.36	3.04	5.12	3.32	5.12	9.08	4.80	2.68	3.80	1.06	1.80	10,86	7.16	1.16	24.62	13.48	5.38	3.94	9.26	2.30	5.90
Course.sand	0,5	5.80	24.00	2.20	3.82	0,92	3.82	15.20	1.82	7.84	1.16	0,24	0,24	4.92	13.70	0,56	15.64	25.92	32.48	4.74	1.06	0,48	10.26
Total		103.20	101.30	101.70	102.40	101.08	102.38	103.80	101.44	97.14	99.62	101.66	102.18	103.36	102.82	102.40	103.06	100,42	99.84	102.44	101.22	100,80	101.74
Silt/clay content		24.00	30.00	22.00	40.00	30.00	40.00	20.00	34.00	62.00	40.00	34.00	16.00	22.00	34.00	28.00	20.00	20.00	30.00	34.00	26.00	40.00	30.76
Sand content		79.20	71.34	79.66	62.38	71.08	62.38	83.80	67.44	35.14	59.62	67.66	86.18	81.36	68.82	74.40	83.06	80,42	69.84	68.44	75.22	60,80	70.90

APPENDICES

APPENDIX A: SEGMENTS CHARACTERISTICS

Segments	Latitude	Longitude	Vegetation classes	Bank erosion weights	Dams	Gullies weights	Tributaries	Net sediment source weights	Vegetation scores	Bank erosion scores	Gully scores
1	-29.456783	26.73568333	1	11	0	8	1	39	Grasses, no bushes or trees	Large	Moderate
2	-29.424717	26.69895000	3	12	2	6	0	18	Grasses, bushes and trees	Large	Moderate
3	-29.420933	26.69991667	3	13	0	5	0	18	Grasses, bushes and trees	Large	Small
4	-29.337583	26.63825000	2	4	1	2	1	26	Grasses and bushes (patched)	Small	Small
5	-29.274800	26.61538333	4	2	0	50	0	52	Bushes and trees (congested)	Small	V Critical
6	-29.210200	26.61710000	2	4	0	32	1	56	Grasses and bushes (patched)	Small	V Critical
7	-29.170917	26.59283333	4	3	0	35	1	58	Bushes and trees (congested)	Small	V Critical
8	-29.133750	26.56926667	3	6	1	65	1	91	Grasses, bushes and trees	Moderate	V Critical
9	-29.094250	26.52476667	3	2	0	11	0	13	Grasses. Bushes and trees	Small	Large
10	-29.079300	26.47950000	4	2	1	3	1	25	Bushes and trees (congested)	Small	Small
11	-29.052500	26.45851667	4	6	1	7	1	33	Bushes and trees (congested)	Moderate	Moderate
12	-29.008183	26.39845000	4	8	1	2	1	30	Bushes and trees (congested)	Moderate	Small
13	-28.978450	26.38845000	4	11	0	2	0	13	Bushes and trees (congested)	Large	Small
14	-28.948950	26.31821667	2	12	1	2	1	34	Grasses and bushes (patched)	Large	Small
15	-28.938867	26.28940000	2	2	0	4	1	26	Grasses and bushes (patched)	Small	Small
16	-28.930417	26.26351667	2	16	0	4	0	20	Grasses and bushes (patched)	Serious	Small
17	-28.875617	26.22561667	3	3	1	2	1	25	Grasses, bushes and trees	Small	Small
18	-28.855150	26.19488333	4	8	1	19	1	47	Bushes and trees (congested)	Moderate	Serious
19	-28.808033	26.11066667	2	2	1	3	0	5	Grasses and bushes (patched)	Small	Small
20	-28.820933	26.05313333	2	2	1	3	0	5	Grasses and bushes (patched)	Small	Small
21	-29.056517	26.46943333	3	4	1	7	0	11	Grasses, bushes and trees	Small	Moderate
22	-29.048017	26.43033333	4	3	1	8	0	11	Bushes and trees (congested)	Small	Moderate
23	-28.976417	26.38126667	4	8	3	8	0	16	Bushes and trees (congested)	Moderate	Moderate
24	-28.958633	26.34436667	2	5	0	15	0	20	Grasses and bushes (patched)	Small	Large
25			4	6	0	8	0	14	Grasses, bushes and trees	Moderate	Moderate
26			4	9	2	30	1	59	Grasses, bushes and trees	Moderate	V Critical
27	-28.887883	26.24065000	3	10	1	36	0	46	Grasses, bushes and trees	Moderate	V Critical
28	-28.845750	26.19090000	4	6	0	7	0	13	Bushes and trees (congested)	Moderate	Moderate
29	-28.840700	26.15471667	3	1	1	14	0	15	Grasses, bushes and trees	Small	Large
30	-28.811767	26.13941667	2	3	1	13	0	16	Grasses and bushes (patched)	Small	Large
31	-28.804983	26.09870000	4	2	1	6	0	8	Bushes and trees (congested)	Small	Moderate
32	-28.824150	26.06546667	3	3	0	7	0	10	Grasses, bushes and trees	Small	Moderate
33	-28.876083	26.00370000	3	2	1	6	0	8	Grasses, bushes and trees	Small	Moderate
34	-29.046850	24.57750000	4	2	2	3	0	5	Bushes and trees (congested)	Small	Small
35	-29.051783	24.51430000	3	4	3	3	0	7	Grasses, bushes and trees	Small	Small
36	-28.999483	24.41951667	4	5	3	4	0	9	Bushes and trees (congested)	Small	Small