Assessing soil erosion associated with main roads in south-eastern South Africa

Khoboso Seutloali

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ABSTRACT

Construction of linear infrastructure such as roads is increasing worldwide for the provision of efficient transportation of both humans and commodities. However, roads have been widely recognised as significant causes of increased soil erosion due to their influence on the hydrologic and geomorphic processes through the modification of natural hill-slope profiles, the construction of cut and fill embankments as well as impervious road surfaces that concentrate runoff. Accelerated soil erosion due to roads is of particular concern since the associated environmental impacts have economic ramifications related to water treatment and soil rehabilitation. In the light of the above, a better understanding of road-related soil erosion is required to guide environmentally sustainable future developments and erosion control efforts. The present study assesses soil erosion associated with main tar roads in the south-eastern region of South Africa.

The first part of the study provides an overview of the linkages of roads with soil erosion by water, related structural designs that facilitate soil erosion processes as well as available approaches for assessing road-related soil erosion and the available erosion control techniques. Secondly, the study focuses on exploring the characteristics (i.e. gradient, length, and vegetation cover) of degraded and non-degraded roadcuts with a view to understanding why some roadcuts are degraded while others are not. Moreover, the study investigates the relationship between the characteristics of the roadcuts and the dimensions (i.e. width and depth) of the rills. Results show that degraded roadcuts are steeper, longer and have a lower percentage of vegetation cover when compared to non-degraded roadcuts. The results further show that there is a significant relationship between the width and depth of the rills, and the slope gradient and percentage of vegetation cover of the roadcuts. These results prompted the need to evaluate the volume of soil loss, using rill dimensions on roadcuts as well as an assessment of the relationship between the volume of soil loss and the soil properties. Results show that soil loss correlates significantly with all the rill dimensions, and the rill depth is the foremost variable in calculating rill volume than the rill width and length. In addition, the results show that there is a significant relationship between the volume of soil loss and the soil properties of the roadcuts.

The study further used remotely sensed data to assess gully erosion related to road drainage release and examined the relationship between physical and climatic factors (i.e. road contributing surface area, vegetation cover, hillslope gradient and rainfall) and the volume of gullies. The results indicate that the road contributing surface area, vegetation cover and hillslope gradient have a significant contribution and influence on the size of the gullies along major armoured roads. Moreover, the results show that remote sensing technologies have the capability to investigate road-related gully erosion where detailed field work remains a challenge due to economic and time constraints.

Finally, in order to evaluate the effectiveness of soil erosion control methods along the roads, the study investigates the performance of different soil erosion control methods utilised on the roadcuts. It was observed that most of the slope stabilisation methods are successful in controlling soil erosion while the majority of drainage control methods performed poorly. The results show that good performance is related to vegetation re-establishment, while poor performance may be attributed to improper application, lack of inspection and maintenance. Overall, the study provides an understanding of erosion related to the post construction phase of roads. In this regard, it is expected that the results of this study will contribute to the management of roads from the soil erosion perspective through appropriate interaction with the South African National Roads Authority (SANRAL). It is hoped that this work will lay the foundation for environmentally sustainable road construction, maintenance and the formulation of effective soil erosion control measures in the future.

PREFACE

The present study was undertaken with the aim of understanding soil erosion associated with main roads in the south eastern region of South Africa. The approach used in this study was a succession of independent but related papers that form different chapters of the thesis. The thesis comprises seven chapters in total, with five chapters conceptualised as stand-alone research articles that address each of the objectives listed in Section 1.5.

The articles making up chapter two to five have been sent to peer reviewed international journals: one is currently in press (Environmental Research Journal), one has been published as a discussion paper (Solid Earth), one in revision (Geocarto International) and two in review (Journal of Geographical Sciences). Each article can be read independently from the rest of the thesis but draws conclusions linked and relevant to the work as a whole. Although the document conforms in general to the University of KwaZulu-Natal style manual, some degree of repetition has been inevitable, given the common thread of the papers.

- Chapter one is the general introduction and a contextualisation of the study.
- Chapter two contains a detailed literature review of the ways in which roads interact with the geomorphic and hydrological processes thereby causing erosion. It also highlights the techniques that are available for investigating road-related erosion as well as the challenges of applying these methods. Available erosion control methods and their effectiveness are also discussed. Based on this discussion, the most effective and economic erosion control method is highlighted.
- Chapter three investigates the relationship between the characteristics of the roadcuts which are: slope gradient, slope length and percentage of vegetation cover and erosion.
- Chapter four assesses soil loss using the survey methodology for rill erosion. Soil loss is also correlated with the soil properties which are: particle size distribution (viz. sand, silt and clay contents), organic matter, exchangeable sodium percentage (ESP) and sodium absorption ratio (SAR).

- In chapter five, gully erosion associated with concentrated road drainage is investigated and the possibility of using geo-information technology in identifying and estimating the volumes of these gullies is explored. The relationship between (1) the road contributing area, drainage discharge hillslope gradient and vegetation cover and (2) the volume of gullies at culvert and mitre drain outlets are also examined.
- Chapter six focuses on exploring the effectiveness of soil erosion control methods. The focus is to analyse the reasons for their success as well as failure.
- Chapter seven provides a synthesis of the research work.

DECLARATION 1

The research work described in this thesis was carried out in the School of Agricultural, Earth and Environmental Sciences, University of KwaZulu-Natal, Pietermaritzburg, from February 2012 to December 2014, under the supervision of Professor Heinrich Beckedahl (School of Agricultural, Earth and Environmental Sciences, University of KwaZulu-Natal; South Africa).

I would like to declare that the research work reported in this thesis has never been submitted in any form to any other university. It therefore represents my original work except where due acknowledgments are made.

Khoboso Seutloali Signed: ________________________ Date: _________________

As the candidate's supervisor, I certify the above statement and have approved this thesis for submission.

Professor Beckedahl Signed: ___________________ Date: _________________

DECLARATION 2-PLAGIARISM

I, Khoboso Seutloali, declare that:

1. The research reported in this thesis, except where otherwise indicated, is my original research.

2. This thesis has not been submitted for any degree or examination at any other university.

3. This thesis does not contain other persons' data, pictures, graphs, or other information, unless specifically acknowledged as being sourced from other persons.

4. This thesis does not contain other persons' writing, unless specifically acknowledged as being sourced from other researchers. Where other written sources have been quoted, then:

   a. Their words have been re-written, but the general information attributed to them has been referenced.
   b. Where their exact words have been used, then their writing has been placed in italics and inside quotation marks, and referenced.

5. This thesis does not contain text, graphics, or tables copied and pasted from the Internet, unless specifically acknowledged and the source being detailed in the thesis and in the references section

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DECLARATION 3- MANUSCRIPTS

1. **Seutloali,** K. E. and Beckedahl, H. R. "A review of road construction-related soil erosion: causes, assessment and control measures", *Earth Sciences Research Journal*. In press

2. **Seutloali,** K. E. and Beckedahl, H. R. 2015. "Assessing the determinants of rill erosion on roadcuts in the south-eastern region of South Africa", *Solid Earth Discuss*, 7, 393-417.

3. **Seutloali,** K. E. and Beckedahl, H. R. "Evaluating soil loss on roadcuts in south-eastern South Africa using rill dimensions and soil properties" *Journal of Geographical Sciences*. In review

4. **Seutloali,** K. E., Beckedahl, H. R., Dube, T. and Sibanda, S. "An assessment of gully erosion along major armoured-roads in south-eastern region of South Africa: A GIS and remote sensing approach. *Geocarto International.* In revision

5. **Seutloali,** K. E. and Beckedahl, H. R. "Evaluating soil erosion control methods on roadcuts" *Journal of Geographical Sciences*. In review

Signed________________________________

DEDICATION

To my beloved parents, sister and precious niece

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This research would not have been possible to complete without the generous help and support of the following individuals and organisations, to whom I would like to extend my sincere gratitude:

I would like to thank God for the gift of life and the ability to do this work.

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CHAPTER ONE

GENERAL INTRODUCTION

1.1 Road construction in context

Road construction is one of the most important features of economic development worldwide (Wilkie *et al.*, 2000; Fedderke *et al.*, 2005). The surface of the earth is traversed by over 32 million kilometres of roads (Taylor and Goldingay, 2010) for the provision of effective transportation of both humans and merchandise (Bochet *et al.*, 2010). Roads are essential for the development and maintenance of economic activity that is crucial for the quality of modern day life (Lugo and Gucinski, 2000; Demir, 2007). For instance, the economic growth in Spain has been ascribed to the improvement of roads (Cerdà, 2007). Similarly, in many regions of China, the extensive road network has been constructed following rapid economic development (Xu *et al.*, 2006). Zawdie *et al.* (2002) reported that roads have been important for economic growth in Sub-Saharan Africa. Specifically, road construction and infrastructural development are some of the most significant features of the South African economic development since the 1920s (Fedderke *et al.*, 2005). While road construction brings about much needed economic development, the associated negative environmental impacts such as the initiation of soil erosion have become more obvious yet are often ignored in the perception that it is 'for a greater good'.

Recent studies have shown that the environment is under threat from soil erosion due to road construction activities as well as features associated with roads (Ramos-Scharron and Macdonald, 2007; Jordan and Martinez-Zavala, 2008). A number of studies have investigated soil erosion related to roads in South Africa (Beckedahl *et al.*, 1998; Moodley *et al.*, 2011; Seutloali, 2011). For instance, Moodley *et al.* (2011) investigated the role of unpaved road surfaces on runoff and sediment generation in a forested catchment in New Hanover, South Africa, while Seutloali (2011) assessed the possibility that this erosion may result in surface water pollution. However, only a few studies have sought to understand accelerated soil erosion due to road drainage (Beckedahl and de Villiers, 2000). Moreover, knowledge on the extent of erosion on roadcuts, as well as the effectiveness of erosion control methods used on roadcuts is still rudimentary. In that regard, there is still a need to fully understand the nature and extent of road-related erosion as well as the performance of the soil erosion control methods in use.

1.2 Understanding soil erosion associated with roads

Soil erosion associated with roads results from the adverse environmental changes (particularly those related to the surface hydrology) caused by road construction. Road construction involves large amounts of earth movement and soil disturbance (Weindorf *et al.*, 2013). This involves cutting through the hillslope profile creating cut and fill embankments (Laurance *et al.*, 2009) as well as scraping of the land surface, removal of vegetation cover and soil compaction for the roadbed (Efta, 2009). The resultant features of roads, in the long run, modify the processes that control storage and distribution of water on the landscape (Ramos-Scharron and Macdonald, 2005) resulting in increased frequency and magnitude of surface runoff that may induce high erosion rates (Macdonald and Coe, 2008). Erosion may be induced on different parts of the road prism including the roadcut, fill embankments (Macdonald and Coe, 2008) and the hillslope where concentrated road drainage is dispersed through culverts or mitre drains (Montgomery, 1994; Croke and Mockler, 2001; Jungerius *et al.*, 2002). The risk of erosion is further worsened in areas with high intensity rainfall (Bracken and Truong, 2000).

Erosion related to roads is likely to increase due to extensions of the road network over time and literature shows that there are associated environmental effects. For example, Croke and Mockler (2001) stated that water pollution can occur as a result of sediment delivery to stream channels due to gully erosion resulting from concentrated road drainage. Furthermore, Osorio and De Ona (2006) indicate that degradation from soil erosion on roadside slopes could lead to slope instability. Therefore, road related erosion, if not well managed, can lead to devastating economic costs related to water treatment and soil rehabilitation (Sutherland and Ziegler, 2007). Soil erosion studies in South Africa have been largely limited to agricultural and pastoral land (eg, Kakembo and Rowntree, 2003; Sonneveld *et al*., 2005). However, for an effective soil erosion control aimed at minimising the environmental and economic costs of soil erosion in general, there is a need to understand road-related soil erosion.

1.3 Evaluation of soil erosion associated with roads

For an assessment of road related erosion to be effective, a sound understanding of the road prisms (i.e. the road surface as well as cut-and-fill embankments) is required. Knowledge of these features would facilitate measurement of the nature and extent of erosion and the selection of an appropriate soil erosion evaluation technique. Consequently, the challenge is to investigate the determinants of erosion on or due to these features, and then relate the levels of erosion to different onsite characteristics in order to recommend the appropriate soil erosion control measures.

1.3.1 Definition of road features

A road usually comprises either all or some of the following features which are: the road surface, cut and fill embankments, the drain or ditch, and the culvert or mitre drain (Fu *et al.*, 2010). The road surface (in the present context a bitumen or tar covering of the roadbed) provides an impermeable layer that has the potential to generate surface runoff, and allow surface water to runoff rapidly, a condition unusual for undisturbed soils (Wemple, 1994). Roadcuts are steep slopes on the side of the road created by excavation (Fu *et al.*, 2010) while the roadfill embankments are constructed by heaping and compacting soil materials from adjacent areas (Tormo *et al.*, 2007). Roads often require roadside ditches to route accumulated runoff from the road bed and intercepted subsurface flow by the roadcuts to culverts. The roadside ditch is a drainage structure alongside the road that channels runoff (Fu *et al.*, 2010). Ditch-relief culverts and mitre drains discharge surface runoff from the roadside ditch to the hillslope below the road (Wemple, 1994).

1.3.2 Procedures for investigating road related soil erosion

An understanding of the linkages between roads and soil erosion is necessary to assist in environmentally sustainable road construction. Lack of adequate understanding of the relevant erosion processes could lead to treatment of the symptoms of erosion rather than the underlying causes (Macdonald and Coe, 2008). A wide variety of methods are available and have been used to assess road related soil erosion. Selection of a suitable method is determined by the component of the road to be examined. These methods are: field runoff plots using rainfall simulation (Arnáez *et al.*, 2004; Sheridan *et al.*, 2008), volumetric survey of soil erosion features (Jungerius *et al.*, 2002; Bewket and Sterk, 2003; Sidle *et al.*, 2011) and the use of soil erosion prediction models (Elliot and Tysdal, 1999; Megahan *et al.*, 2001). However, runoff plots and soil erosion prediction models for assessing road related erosion face some challenges. Runoff plot methods involve expensive instrumentation (Bewket and Sterk, 2003), and lead to an inadequate understanding of the actual erosion process since the runoff plot conditions are homogenous as opposed to diverse natural field conditions (Moodley *et al.*, 2011). Moreover, runoff plots are prone to vandalism especially in the southern African condition. On the other hand, the problems with models are: complexity, cost of development and data availability (Seutloali, 2011). Moreover, models are often calibrated based on data derived from United States and European conditions (Barrett *et al.*, 1998) rather than the southern African context, primarily due to paucity of locally available data, hence their application is questionable. Consequently, volumetric erosion survey is regarded as a good alternative approach to soil erosion research since it is fast, cheap and is conducted under actual natural conditions (Bewket and Sterk, 2003).

1.4 Study objectives

From the discussion above, the main aim of this study is to understand the nature and severity of soil erosion found along the principal road network of south-eastern South Africa.

The specific objectives of this study are as follows:

1. To provide an overview of the effects of roads on soil erosion by water, and to understand the structural designs that facilitate these soil erosion processes as well as the different approaches that have been used to assess erosion.

2. To investigate the relationship between roadcut characteristics and the nature as well as extent of soil erosion.

3. To evaluate the volume of soil lost through erosion on the roadcuts by utilising a volumetric survey of rills.

4. To investigate the prevalence of gully erosion associated with concentrated runoff generated from the road surface at road drainage release sites using remotely sensed datasets.

5. To identify and evaluate the effectiveness of different soil erosion control methods.

6. To make recommendations as to the effective erosion control mechanisms for the environmentally sustainable construction and maintenance of primary road networks.

1.5 Description of the study area

The study was conducted in the south-eastern part of South Africa within the KwaZulu-Natal Province and the former Transkei region of the Eastern Cape Province (Figure 1.1). The terrain of the area is undulating, with a series of dissected steps that rise from a relatively flat coastal plain in the east of South Africa, to the Drakensberg mountains which reach over 3000 meters above sea level and form the western boundary of the region (Beckedahl, 1996).

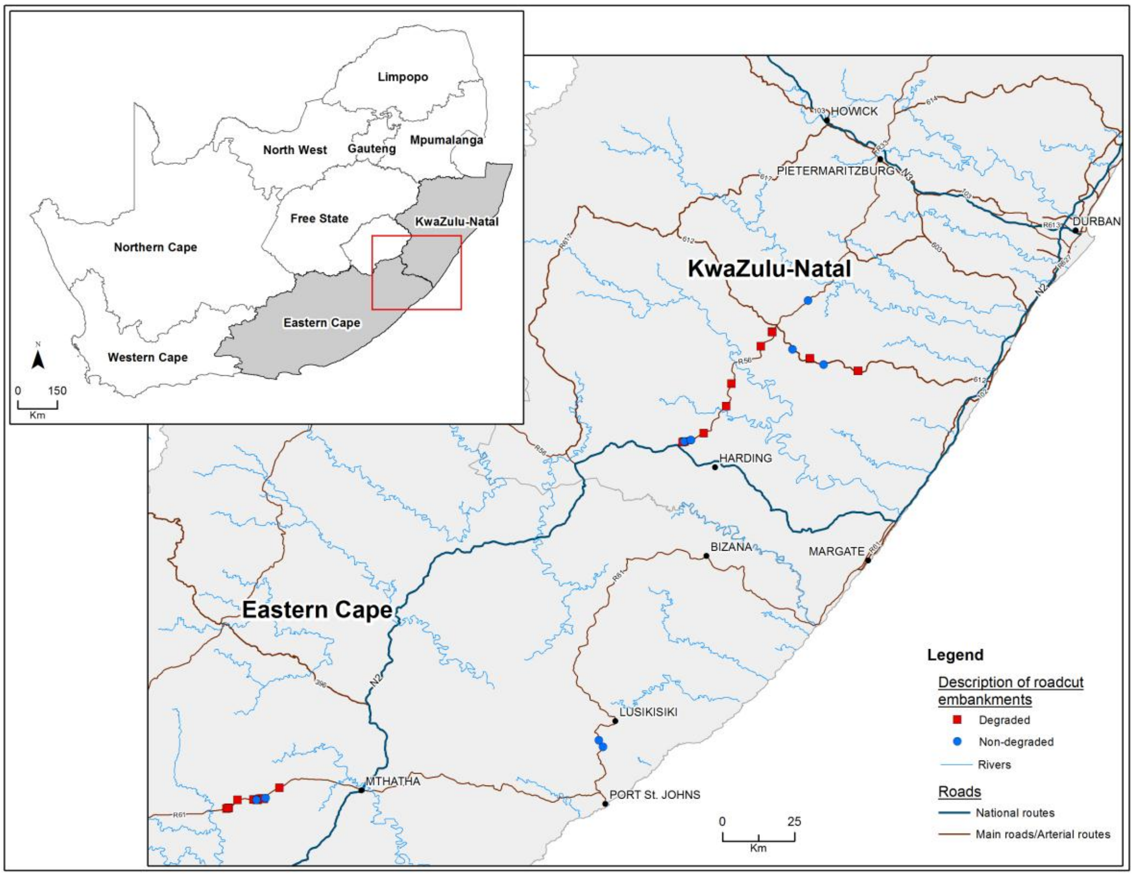

Figure 1. 1: Map showing the location of the study region in the south-eastern part of South Africa and the distribution of roads. Source: Cartographic unit, University of KwaZulu-Natal.

KwaZulu-Natal has a subtropical climate characterised by high humidity, temperatures and rainfall (900-1200 mm) (Fairbanks and Benn, 2000). Summers are warm and wet while winters are cool and dry. The climate changes gradually from the coast to the westerly plateau. On the other hand, the greater part of the Eastern Cape Province is characterised by a sub-humid warm climate with summer dominant rainfall (Jeschke *et al.*, 1990). Rainfall patterns in the study area reflect a variation between 500 mm and 1400 mm, (Madikizela, 2000). This region has among the highest values of rainfall erosivity index (EI_{30}) in southern Africa (see Figure 1.2). The EI_{30} shows the potential ability for rainfall to cause soil erosion (da Silva, 2004). It is the product of the total storm kinetic energy and the maximum 30 minutes rainfall intensity (Le Roux *et al.*, 2008). The biomes of KwaZulu-Natal and Eastern Cape range from coastal tropical forest to temperate transitional forest and grassveld. The geology of the study area mainly consists of sandstones and mudstones of Beaufort and Ecca groups (Beckedahl, 1996). The geology has minor exposures of the Natal Group sandstones and dolerite intrusions. The soil types vary from the lithosols to podzolic and duplex soils of the midlands and coastal belt which are characterised by varying levels of erodibility (Beckedahl, 1996).

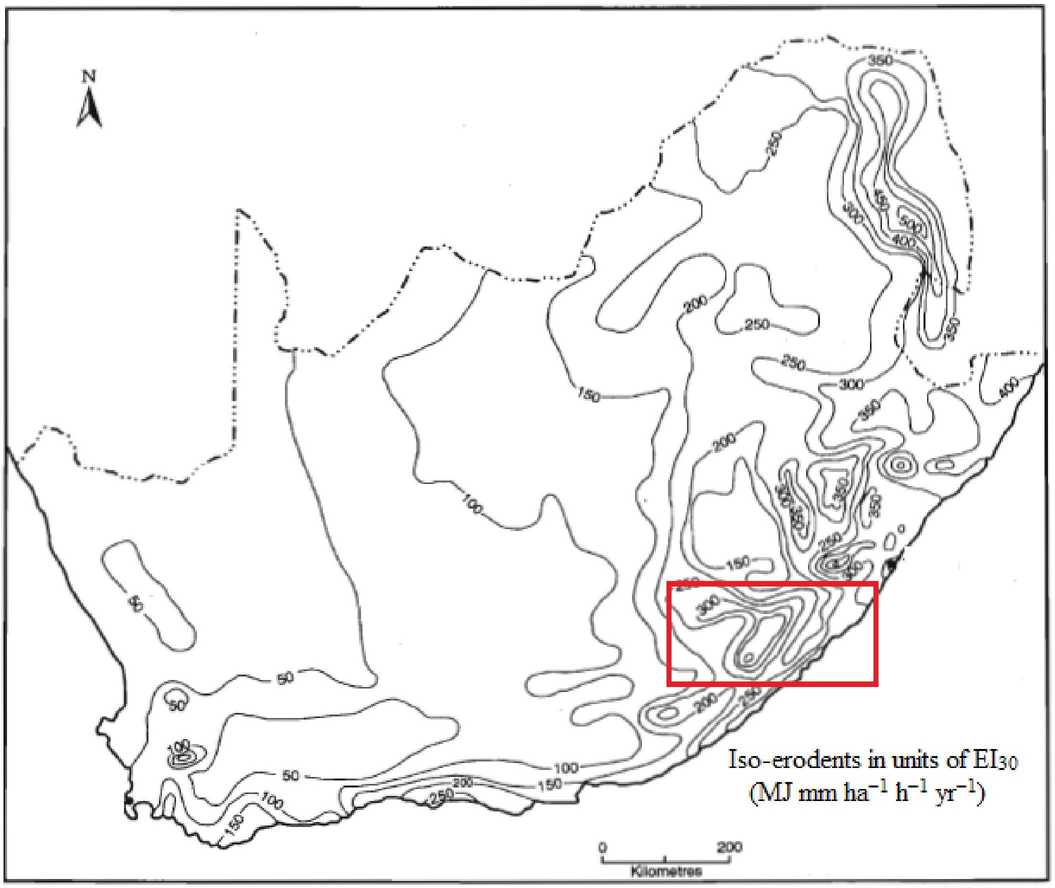

Figure 1. 2: Iso-erodent map showing variability of EI_{30} values in south-eastern South Africa, with higher values in the south-eastern South Africa. Source: Beckedahl (1996) after (Smithen, 1981). The approximate area of study is shown by the red box.

The selection of this area was based on two major reasons: firstly, it is an area with highly erodible soils (Hoffman and Todd, 2000, Le Roux et al., 2007) and high rainfall erosivity

(Beckedahl, 1996) and road construction has provided roadcuts, culverts and mitre drains that discharge concentrated road runoff on the hillslopes below the road, making the area vulnerable to gully erosion, especially where there are no environmentally sustainable land management practices in place. Secondly, there are limited reported investigations that have been carried out in the area, on erosion related to the post construction phase of armoured roads.

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CHAPTER TWO

A REVIEW OF EXISTING RESEARCH ON ROAD-RELATED SOIL EROSION

This chapter is based on:

Seutloali, K. E. and Beckedahl, H. R., (In press) “A review of road -related soil erosion: an assessment of causes, evaluation techniques and available control measures”, *Earth Sciences Research Journal*.

2.1 Abstract

Road construction has increased significantly worldwide in the last decades to meet the demands of the increasing human population and this has led to serious soil erosion problems, the bulk of which is unaccounted for, especially in the developing world. For comprehensive land management decisions and monitoring strategies, a review of work that has been done to assess soil erosion due to roads is critical. This article therefore reviews the causes of road–related soil erosion, assessment methods and available control measures. Specifically, work provides an overview of (i) the linkages between roads and soil erosion; (ii) measurement and prediction of road–related erosion; and (iii) erosion control and rehabilitation techniques. Literature shows that road construction results in hill-slope profile modification, removal of vegetation cover, as well as the formation of steep slopes which are prone to severe erosion. Furthermore, there is a variety of erosion control measures for controlling road–related erosion although no study has demonstrated the method that is cost effective and operational across different landscapes. We are of the view that this study provides guidance in future research on road–related soil erosion across the developing world where sophisticated monitoring techniques are limited due to resource scarcity for assessing large areas.

Keywords: roadcut and fill embankments; road drainage structures; runoff; soil loss; measurement and prediction; revegetation

2.2 Introduction

Road construction has increased significantly worldwide in the last decades for the provision of effective human mobility and transportation of commodities (Bochet *et al.*, 2010). This development has resulted in permanent alteration of the geomorphic and hydrological settings of the landscape leading to increased soil erosion (Ramos-Scharron and Macdonald, 2007). Road construction can lead to the modification of natural hill-slope profiles, the construction of roadcut and fill embankments and impervious roadbeds that concentrate runoff (Jordan and Martinez-Zavala, 2008). Roads concentrate runoff, critical for enhancing hill-slope soil loss and sediment yield which later impairs the quality of surrounding open waterbodies (Lane and Sheridan, 2002; Forsyth *et al.*, 2006; Ramos-Scharron and Macdonald, 2007; Sheridan and Noske, 2007). Lane and Sheridan (2002) in their study observed a water quality deterioration as shown by increased turbidity and total dissolved solids downstream of a road stream crossing. The major sediment source at the road stream crossing was the result of erosion at the road verge and the road fill slopes.

Environmental challenges caused by the accelerated soil erosion due to roads have economic ramifications related to soil rehabilitation and water treatment. It is therefore, a necessity to provide an overview of literature on road-related soil erosion for a better understanding of the causes and methods of assessment that have been considered so as to (1) guide future development; and (2) provide the necessary guidance and informed recommendations on possible effective and cheap monitoring approaches and erosion control efforts especially in resource scarce environments. This review therefore seeks to provide an overview of: (i) the effects of armoured roads on soil erosion by water, (ii) related structural designs that facilitate soil erosion processes, and (iii) available approaches for assessing road-related soil erosion and the available erosion control techniques.

So far, to the best of our knowledge, a limited number of studies have been done to assess soil erosion related to paved roads. Previous studies on road–related erosion have been dominated by the work on forest roads (i.e. unpaved roads) which include those by

Burroughs and King (1989) who addressed the potential for reduction of onsite sediment production by different treatments on different components of the forest road prism. Croke and Hairsine (2006) reviewed the interaction of forest road and track network with both sediment and runoff delivery in managed forests. The review by Macdonald and Coe (2008) discussed the underlying processes of forest roads sediment production from surface erosion and land sliding. Although Baird *et al.* (2012) also reviewed forest road erosion, their focus was on the processes of erosion and sediment delivery from these roads, whereas the other studies either considered land-sliding or the process of runoff from the forest road network only. The limitation of the above-mentioned reviews is that none addressed the post construction case of armoured roads except focusing on erosion from unpaved forest roads. Furthermore, none of the studies conceptualized assessment of road-related erosion, as well as its control.

2.3 Road-related soil erosion

Road construction creates numerous roadcut and fill embankments, as well as ditch relief or culvert sites (Figure 2.1) that contribute to runoff and high sediment production that cause extreme land degradation (Ramos-Scharron and Macdonald, 2007). Roadcut and fill embankments have bare and steep gradients that cause the generation of runoff and sediment yield (Bochet and García-Fayos, 2004). Lack of vegetation cover also intensifies soil detachment by raindrops and proliferates susceptibility to erosion as a result of reduced cohesion and shear strength of the soil (Jankauskas *et al.*, 2008). Similarly, steep gradients increase erosion on these slopes due to reduced water infiltration and increased runoff accumulation (Arnáez *et al.*, 2004; Cerdà, 2007).

Numerous studies have documented soil erosion on roadcut and fill embankments (Megahan *et al.*, 2001; Arnáez *et al.*, 2004; Jordan and Martinez-Zavala, 2008; Xu *et al.*, 2009). For example, a study by Arnáez *et al.* (2004) recorded a significant generation of runoff and sediment from roadcuts and fillslopes in the Iberian Range, Spain. Roadcut soil loss rates exceeded those from the fill-slopes by 16 times and this was attributed to the steep gradients, presence of embedded gravels and low vegetation cover. Similarly, Jordan and Martinez-Zavala (2008) recorded a total soil loss of 106 g m^{-2} and 17 g m^{-2} from roadcut and side-cast fills respectively in southern Spain. The highest erosion rate was observed on the roadcuts due to steep slopes, low vegetation cover and the presence of loose colluviums. Moreover, Megahan *et al.* (2001) evaluated the effects of slope gradient, slope length, slope aspect, rainfall erosivity and ground cover density on erosion on the roadcuts in Idaho, USA. The multiple regression analysis showed that slope gradient was the most significant of all site variables in affecting roadcut erosion. Xu *et al.* (2009) on the other hand investigated the effects of rainfall and slope length on runoff and soil loss on the Qinghai-Tibet highway side-slopes in China and found that rainfall intensity correlated with sediment concentration and soil loss, while soil loss decreased with increasing slope length. In summary these studies highlight that slope properties (viz. slope gradient and length, vegetation cover and soil properties, particularly soil texture) of the roadside embankments are critical in determining the degree of soil erosion along these areas.

Roads initiate soil erosion through drainage structures diverting water from their impervious surfaces as well as from roadcuts. Road surfaces (including unamoured roads) are responsible for increasing runoff generation (Ziegler and Giambelluca, 1997). Furthermore, the road surfaces transect the hillslope hydrology, creating the need for draining the roadcut and road surface through culverts at regular intervals (as indicated by point 1, in Figure 2.1), with the consequential change from diffuse surface flow downslope to concentrated flow. Extensive surface erosion may occur where this concentrated flow is discharged down-slope at discharge points (point 2 and 3 in Figure 2.1). Geomorphic impacts of concentrated runoff from road drainage have been documented by numerous studies (Montgomery, 1994; Kakembo, 2000; Beckedahl and de Villiers, 2000; Jungerius *et al.*, 2002).

Montgomery (1994) conducted a field survey of road drainage concentration in the western United States and observed that the discharge of road surface concentrated runoff and of intercepted subsurface flow result in initialization and enlargement of a gully and slope instability below the drainage outfall. Gully initiation was related to ground slope and contributing area thresholds. Kakembo (2000) reported a case of ephemeral stream incision triggered by runoff concentration through a series of railway culverts on a steep hillslope at Kwezana, Eastern Cape, South Africa and concluded that concentrated runoff coupled with the steep slope of the drainage discharge area, and the rainstorms of high magnitude influenced gully initiation. Although not a case study of roads, the scenario is similar in that in this case too, the slope hydrology is disrupted and concentration of runoff initiated gullies and triggered hillslope instability. Jungerius *et al.* (2002) reported gully formations where concentrated surface water was diverted to the verges alongside the road in West Pokot, Kenya. The study found that gully formation is influenced by the steep slopes, lack of vegetation cover, torrential rainfall and the fine grained soils of the alluvial fans. Beckedahl and de Villiers (2000) investigated the causal relationship between road drainage and pipe erosion in the Eastern Cape province, South Africa. Their findings showed that soil pipes and gullies developed where road drainage resulted in high concentration of surface water on sensitive or dispersive soils. These studies have shown that erosion initiation at road drainage discharge sites is influenced by the contributing area, slope steepness, rainfall intensity and soil properties. The studies by Kakembo (2000) and Montgomery (1994) however, did not include the estimation of the quantity of soil loss in their agenda. Investigations of the impact of concentrated road runoff on soil erosion, to be complete and comprehensive, should consider also an estimation of the amount of soil loss rather than simply dwelling only on the contributing factors. These estimations are necessary as they could provide clear and detailed evidence of the effects of concentrated road runoff discharge on the actual soil loss.

Having discussed the possible effects of road construction on soil erosion, it is important to highlight the methods that can be utilized to investigate road–related erosion. This knowledge will help for accurate assessment of erosion levels and soil loss along the road networks.

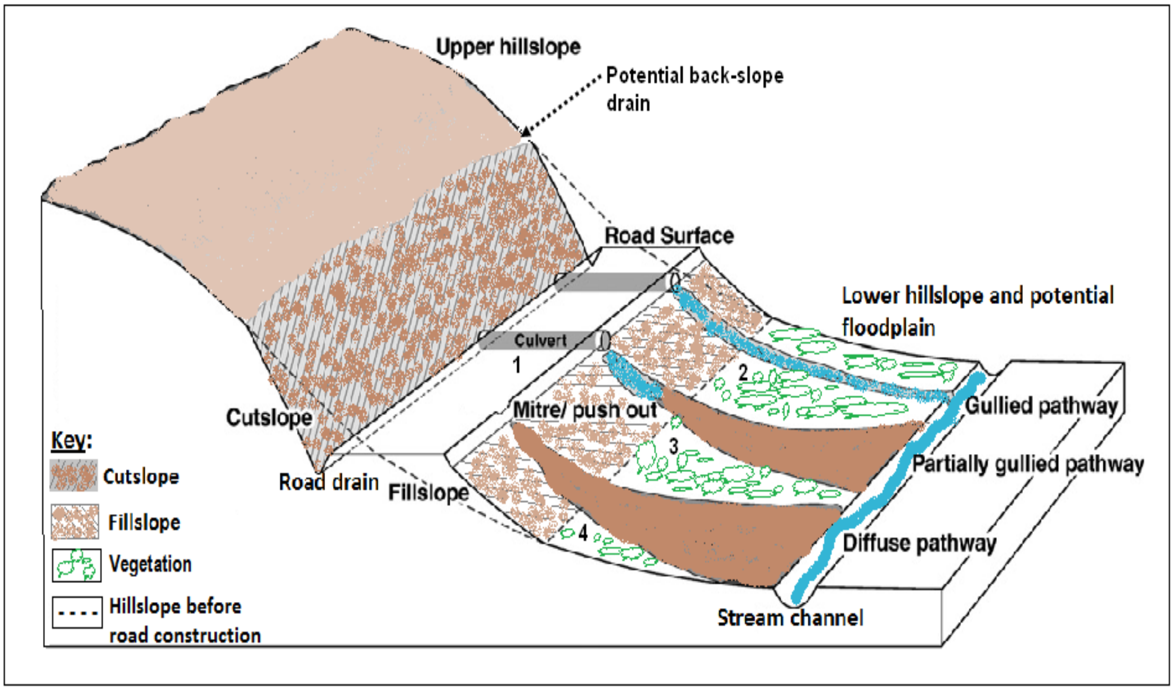

Figure 2. 1: A typical cut and fill road cross section and features. The numbers one (1) to four (4) refer to potential impacts, and these are discussed in the text. Adapted from (Fu *et al.*, 2010).

2.4 Methods of assessing road–related soil erosion

2.4.1 Road–related soil erosion field measurement techniques

Available field methods of measuring road-related erosion have been principally based on rainfall simulation and on volumetric surveys of erosion features. The choice of a particular technique primarily depends on the part of the road component to be monitored (Table 2.1). Rainfall simulation method has been widely used to explore runoff and soil loss processes related to roadcut and fill slopes, as well as unpaved road surfaces in many parts of the world (Table 2.1). Rainfall simulators create controlled rainfall events (Jordan and Martinez-Zavala, 2008) and their design depends on the type of experiments to be carried out (Clarke and Walsh, 2007). Control of rainfall allows determination of the relationship between soil loss and rainfall parameters (Lascelles *et al.*, 2000) as well as generation of runoff and soil loss under repeatable conditions (Hamed *et al.*, 2002). Moreover, in semi-arid regions, with high rainfall variability and recurrent droughts, rainfall simulation could be useful (Cerdà, 2007). However, rainfall simulation is uncertain for extrapolating results to larger scale (Arnáez *et al.*, 2004) and also underestimates soil loss as compared to natural rainfall as it supplies a constant rainfall intensity (Boix-Fayos *et al.*, 2006) and short duration rainfall (Jin *et al.*, 2008). Nevertheless, simulation results remain useful for comparative purposes (Foster *et al.*, 2000; Jordan and Martinez-Zavala, 2008) and for forward planning, despite challenges of underestimating loss and limitation to small scale applications.

On the other hand, the volumetric survey of erosion features for assessing road-related soil erosion involves the use of measured dimensions (viz. lengths, widths and depths) of the erosion features either directly in the field or from the use of photographic images to estimate soil loss (Okoba and Sterk, 2006). These dimensions are then utilized to calculate the volume of the erosion features excavated, which is equivalent to the volume of soil lost (Hagmann, 1996). Although actual soil loss is underestimated since inter-rill erosion is excluded when measuring pipe, gully and rill erosion, the approach produces the best approximation of erosion (Bewket and Sterk, 2003). A number of studies have been carried out using the volumetric survey of erosion features to estimate soil erosion on roadcut and fill embankments and most of these have focused on measurement of erosion related to concentrated runoff from road culverts (Table 2.1). Other studies such as that of Bochet and García-Fayos (2004), in Valence, Spain, used an erosion index for rill and gully erosion to determine its severity on motorway slopes. The erosion index is based on the percentage cover of erosion on the sampling area. However, unlike other studies based on quantitative estimation of erosion, this semi-quantitative estimation of erosion did not reveal the effect of aspect on erosion intensity and this was attributed to the fact that this method might have not been precise enough to detect such differences. Although field methods provide the necessary understanding of erosion processes, the obtained results are however, difficult to generalize due to the complex interaction of erosion processes and field conditions (Ande *et al.*, 2009). Prediction of road-related erosion could, therefore, help consider the complex interactions that affect erosion rate.

2.4.2 Modeling of road-related soil erosion

Soil erosion models vary from simplified procedures, such as the Universal Soil Loss Equation (USLE) to more complex methods requiring a series of input parameters, such as Water Erosion Prediction Project (WEPP) (Oliveira *et al.*, 2012). USLE, and its modifications, the Revised Universal Soil Loss Equation (RUSLE) computes the average annual soil loss caused by rill and inter-rill erosion by multiplying the natural factors (rainfall erosivity-R, erodibility-K, slope length and steepness-LS) and anthropogenic factors (cover and management-C, and conservation practices-P) (Angima *et al.*, 2003; Oliveira *et al.*, 2012). Literature has shown that USLE/RUSLE approaches give better estimates for erosion on an overall basis. Oliveira *et al.* (2012) state that the USLE/RUSLE provides a good approach for soil loss prediction since it is applicable in terms of required input data, and the obtained soil loss estimates are reliable. However, the application of this model is based upon erosion rates from landscapes larger than road plots hence application for roads is at a smaller scale than for which it was intended (Riedel, 2003).

In contrast to the USLE/RUSLE, the WEPP model was developed to provide a spatial and temporal distribution of soil loss (Clinton and Vose, 2003; Baird *et al.*, 2012). This model utilizes climate, infiltration, water balance, soil chemistry, plant growth and residue decomposition, tillage and consolidation to predict soil erosion deposition and sediment delivery (Clinton and Vose, 2003; Baird *et al.*, 2012). WEPP model is applied to roads by including multiple road features such as road surface, cut-slope, ditch, fill-slope and lower hillslope (Elliot *et al.*, 1995; Forsyth *et al.*, 2006; Fu *et al.*, 2010; Cheng *et al.*, 2013). The road features are modeled separately by defining them as different overland flow elements with unique soil and vegetation parameters assigned (Fu *et al.*, 2010). Although some models exist for predicting road-related erosion, these are primarily used to predict erosion from the road surfaces (Forsyth *et al.*, 2006; Sheridan *et al.*, 2006) and few studies have focused on modelling erosion on roadside slopes and erosion due to road drainage ditches/culverts (Elliot and Tysdal, 1999; Megahan *et al.*, 2001) (see Table 2.2).

Erosion models, however, suffer from a range of problems (Barrett *et al.*, 1998). Firstly, the model development was often based on data derived from the United States or European conditions and the application of these models to different climatic and management conditions in other regions has not yet been fully established. Secondly, the models were created for field plot scale and application for large scales is still questionable. Thirdly, the model predictions are not entirely accurate as a result of incomplete knowledge of the entire set of aspects and interaction processes resulting from a limited set of variables. For instance, the disturbance associated with construction frequently exposes the subsoil (or new soil may be brought in from elsewhere) hence the erodibility values along the road will differ to those of the region (Barrett *et al.*, 1998). Therefore, for road applications, these models still require further testing, and modifications to include additional factors specially designed for road erosion (Fu *et al.*, 2010). Measurement of soil erosion using the volumetric survey of erosion features, therefore, could provide a reasonable estimation of erosion (Sidle *et al.*, 2004) and does not involve expensive instrumentation, long lead times and/or sophisticated modeling (Bewket and Sterk, 2003).

Table 2. 1: Overview of the techniques of field measurement of road-related erosion used to date

Road erosion source	Technique	Study Location	Main findings and conclusion	Reference
Cut and fill slopes, and roadbed	Rainfall simulation	Iberian Range, Spain	Erosion measured for cut and fill slopes were consistent with the rates measured using other techniques such as erosion pins. Rainfall simulation however, provided limited information because of the small size of the plot. Nonetheless, the results allowed comparisons of runoff data and erosion in two sectors of the roads; and their relationship with soil properties.	Arnáez *et al.* (2004)
Road batters	Rainfall simulation	New South Wales, Australia	Rainfall simulation demonstrated significant fluctuations in soil loss with time from the road batters investigated and this was attributed to micro-erosion processes. However, small scale rainfall simulation could not replicate large scale erosion processes hence are deemed unsuitable for erosion studies on roads.	Selkirk and Riley (1996)
Road culvert	Volumetric survey of soil pipes	Eastern Cape province, South Africa	Volumetric survey of soil pipes allowed the estimation of the removed soil material. The results however, are approximations, given the inferences made in obtaining them.	Beckedahl and de Villiers (2000)
Cut and fill slopes	Rainfall simulation	Southeastern Australia	Sediment generation rates from rainfall simulation were consistent with the findings from other studies.	Sheridan *et al.* (2008)
Cut and fill slopes	Volumetric survey of gullies	Northern Yunnan Province, China	Provided a simple method for estimation of soil loss on cut and fill slopes although errors in the range of ±10% are likely and could lead to underestimation.	Sidle *et al.* (2011)
Road Culvert	Volumetric survey of roadside gullies	West Pokot, Kenya	Survey of roadside gullies provided a tool that allowed the estimation of the volume of soil lost due to concentrated road runoff and correlation of soil loss to site variables.	(Jungerius *et al.*, 2002)

Table 2. 2: Mathematical models used for predicting road-related erosion.

Erosion source	Model	Study Location	Main findings and conclusion	Reference
Roadcuts	USLE	Idaho, USA	The equation allowed the evaluation of factors that affect roadcut erosion e.g. slope gradient, slope length, slope aspect, rainfall energy, cover, erosion control practices, erodibility and age of the roadcut. The prediction equation could provide a useful tool to land managers to evaluate the risk of roadcut sediment yield for alternative road design practices.	(Megahan *et al.*, 2001)
Ditch, roadcuts and road surface	WEPP	Oregon coast range, western Eugene	WEPP predictions were in close agreement with the observed sediment yield measurements. Although WEPP overestimated erosion in some instances, the predictions give reasonable approximation of sediment yield.	(Elliot and Tysdal, 1999)
Road surfaces	WEPP	New Hanover, South Africa	The model performed well in predicting sediment loss from the road segments. However, the model was unable to account for vegetation cover. Additionally, the model dealt with individual road segments and not the entire road network. Therefore, predicting the entire road network by analyzing individual road segments was complex and time consuming. Nevertheless, WEPP was considered suitable for erosion prediction, although not ideal.	(Moodley *et al.*, 2011)
Cut and fill slopes	WEPP	Southern Appalachian	The predicted average annual sediment yield was within the range of observed sediment yield values. While, the model over predicted sediment yields in some instances, the relatively high model efficiencies that ranged from 0.51- 0.99 showed that the model was adequate in describing sediment yields observed in the field experiment.	(Grace III, 2005)

2.5 Methods used to control road-related soil erosion

Soil erosion control measures, i.e. non-engineering and bio-engineering (e.g., vegetation, soil erosion control blankets, silt fences and geotextiles) and engineering techniques (e.g., diversion drains and LAttice) are formulated to reduce accelerated soil erosion rates on roadside slopes (Rickson, 2006; Xu *et al.,* 2006). This is because roadside slopes have been demonstrated as major contributors towards road-related soil erosion, accounting for 70 to 90% of the total soil loss from the disturbed roadway area (Grace III, 2000). Most of erosion control measures are specifically designed to minimise the contact of rainfall with the soil as well as reduce runoff velocity (De Oña *et al.*, 2009). While these soil erosion control methods are effective in minimising road-related soil erosion, however, some of these methods are failing to meet their intended objectives while others are even expensive to use especially in resource scarce environments.

Amongst all these control methods, vegetation cover is probably the most widely used measure for controlling erosion on roadside slopes (Xu *et al.*, 2006). This is because vegetation cover intercepts rainfall and increases water infiltration (Claridge and Mirza, 1981; Faucette *et al.*, 2006), stabilizes the soil with roots that hold soil particles together (Collison and Anderson, 1996; Bochet and García-Fayos, 2004), and moderates and dissipates the energy exerted by water (Lal, 2001; Ande *et al.*, 2009). Grace III (2000) and Xu *et al.* (2006) emphasised the importance of vegetation cover in reducing soil erosion and their findings are also supported by the inserts above that indicate the importance of vegetation cover on roadside slopes. Grace III (2000) observed a reduction of sediment yield by over 30% on vegetated roadcut and fill slopes compared to the bare roadside slopes and concluded that vegetation has the greatest potential to mitigate soil erosion through stabilizing the roadside slopes. Similarly, Xu *et al.* (2006) found that vegetation provides a long term soil erosion control on roadside slopes and concluded that soil erosion is significantly reduced when vegetation cover is well established.

The effectiveness of vegetation cover to control erosion, however, starts when the vegetation is established (Rickson, 2006) and mature (Vishnudas *et al.*, 2006). For instance, Vetiver grass (*Vetiveria zizanioides* L. Nash) application significantly controls soil erosion and stabilizes the slopes, although it may take at least one year to become fully effective (Sanguankaeo *et al.*, 2003). This implies that a site may be susceptible to erosion during the period when there is no vegetation or immature stage, also making the establishment of vegetation difficult, since there is no immediate and adequate protection (Vishnudas *et al.*, 2006). Additionally, the absence of initial binding material in the slope soils may result in poor vegetation growth (Bhattacharyya *et al.*, 2008). For these reasons, soil erosion control blankets and geotextiles are short-term vegetation cover replacement that have been used to offer immediate soil protection (Smets *et al.*, 2009).

Erosion control blankets reduce runoff and soil erosion by improving soil quality (Bhattarai *et al.*, 2011) and enhancing vegetation (Faucette *et al.*, 2006) that would offer a permanent erosion control. Likewise, geotextiles control rain splash and runoff (Bhattacharyya *et al.*, 2010) and promote a micro-climate for subsequent vegetation growth (Sutherland and Ziegler, 2006). Geotextiles are applied on bare slopes after spreading seed mixture for long-term erosion protection (Sutherland and Ziegler, 2007). Erosion control geotextiles are made from natural or synthetic material (Smets *et al.*, 2009) with synthetic geotextiles dominating the commercial market (Jankauskas *et al.*, 2008). Synthetic geotextiles such as silt fences are used for highway and other construction projects to provide a temporary sediment control (Barrett *et al.*, 1998). Silt fences reduce runoff velocity and filters sediments thereby enhancing sedimentation (Barrett *et al.*, 1998). Silt fences are preferred because they are cheap and easy to install (Robichaud *et al.*, 2001; Wachal *et al.*, 2009). The limitations of synthetic geotextiles however, are that they are non-degradable and may cause soil pollution, and their production may cause air and water pollution (Bhattacharyya *et al.*, 2010). According to Jankauskas *et al.* (2008) however, natural geotextiles constructed from organic materials are more effective in controlling soil erosion since they adhere to the surface’s microtopography and are able to follow slope contours and stay in close contact to the soil (Bhattacharyya *et al.*, 2010). Additionally, natural geotextiles are easily available in many parts of the world, less costly to produce, apply and are environmentally friendly as they are made of biodegradable material (Bhattacharyya *et al.*, 2008).

Some previous studies have evaluated the effectiveness of erosion control blankets and geotextiles in reducing erosion on roadside slopes and found that they reduce soil loss as a result of improvement in vegetation growth (De Oña and Osorio, 2006; Jankauskas *et al.*, 2008; Pengcheng *et al.*, 2008; Bakr *et al.*, 2012). Bakr *et al.* (2012) examined the influence of compost/mulch on storm water runoff rates on highway embankments in Louisiana. They found that compost/mulch was effective for soil erosion control since it increased crop cover and reduced soil loss. Others such as Pengcheng *et al.* (2008) evaluated the application of sewage sludge compost on highway embankments in China and observed an improvement of soil quality parameters, increased growth of ryegrass and a reduction in volume of runoff and soil loss. Similarly, Osorio and De Ona (2006) observed that compost application on road embankments in southern Spain increases vegetation cover and reduces soil loss. Additionally, it was found that soil loss decreased with addition of greater quantities of compost. Jankauskas *et al.* (2008) investigated the use of palm-leaf geotextiles to control erosion on roadside slopes in Luthuania. They found that soil erosion from bare fallow soil was reduced by 91.15 – 94.8% and this was attributed to the multiple benefits such as soil conservation and improved soil moisture that encouraged better plant growth.

On the other hand, engineering soil erosion control techniques (e.g. diversion drains and LAttice structures) like non-engineering methods, also reduce erosion on roadside slopes by diverting runoff away from the surface of the roadside slope (Claridge and Mirza, 1981). These techniques, however, do not provide a protective layer on the surface of the roadside slope, hence soil detachment from direct rainfall impact could still occur. The combination of engineering and vegetation measures could therefore provide an effective method in reducing runoff and direct rainfall impact thereby reducing soil loss on roadside slopes (Xu *et al.*, 2006).

On the basis of the above discussion, the most effective and economic soil erosion control strategy is re-vegetation. This is because vegetation cover provides a cheap long-term erosion control (Benik *et al.*, 2003), requires less maintenance than complex engineering structures (Montoro *et al.*, 2000) and improves the landscape aesthetic value (Albaladejo Montoro *et al.*, 2000). Hence, soil erosion control through the establishment of a dense vegetation cover is a priority for restoration of roadside slopes (García-Palacios *et al.*, 2010) as illustrated in Figure 2.2a. On the other hand, it can be observed in Figure 2.2b that areas without vegetation cover are prone to erosion. While the use of soil erosion control measures has been widely recognised and investigated, these investigations have, in most cases, focused on the non-engineering and bio-engineering techniques, and less attention has been given to engineering measures although they could provide an effective erosion control on roadside slopes (Xu *et al.*, 2006). Therefore, there is a need to assess the effectiveness of engineering measures for erosion control on roadside slopes.

Figure 2. 2: (a) Successful application of vegetation cover to control erosion on a roadside slope and (b) signs of erosion on a roadside slope due to the absence of vegetation cover.

2.6 Conclusion

Roads and road construction result in soil erosion due to the impacts of rainfall affecting geomorphic and hydrologic processes. Research has shown that the creation of roadcut and fill embankments with steep slopes and little vegetation cover, as well as the concentration of runoff from the road surface and intercepted subsurface flows influence the hydrologic and geomorphic processes. Roadcuts, however, are the major sources of erosion than other parts of the road with slope gradient being the most important factor influencing soil erosion. A variety of techniques are used to investigate road-related erosion, ranging from field measurements to soil erosion prediction models. These methods could assist in understanding the nature and severity of road-related erosion and can help guide future development and erosion control efforts. However, besides the strengths of erosion measurement methods, soil erosion prediction models, although appropriate for predicting soil loss for the field plot scale, have challenges when applied to small plots. Therefore, there is a need for further testing and modification of soil erosion prediction models for road application.

It has been shown in the literature that soil erosion control techniques have the potential to reduce runoff and soil loss. Numerous studies that have investigated the effectiveness of soil erosion control techniques utilised on roadside embankments showed that the most effective methods are those that promote revegetation and reduce both velocity and quantity of runoff. Since the extent of road networks is ever-increasing, lessons learned from this research may be applied in the future construction of road systems. As such, research still needs to be done (i) to fully understand the underlying determinants of soil erosion related to road design and construction to limit the effect from embankments; (ii) to quantify road-related soil loss; (iii) to evaluate the effectiveness of erosion control methods on both roadcut and fill embankments; and (iv) to identify new methods such as remote sensing technologies, to try to improve soil erosion mapping along roads for future monitoring and management strategies. This review therefore provides the necessary insight and inspiration to geomorphologists, road engineers and environmentalists to move towards identifying the most suitable, cheap and readily available techniques for assessing and controlling soil erosion, necessary for reliable and informed approaches for monitoring and managing road-related soil erosion across the world, especially in under resourced countries.

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CHAPTER THREE

ASSESSING THE DETERMINANTS OF RILL EROSION ON ROADCUTS

This chapter is based on:

Seutloali, K. E. and Beckedahl, H. R. 2015. “Assessing the determinants of rill erosion on roadcuts in the south-eastern region of South Africa”, *Solid Earth Discuss,* 7, 393-417.

3.1 Abstract

Erosion of roadcuts is a concern due to their potential to cause environmental degradation which has significant economic costs. It is therefore critical to understand the relationship between roadcut characteristics and soil erosion for designing roadcuts that are less vulnerable to erosion and to help road rehabilitation works. This study investigated the characteristics (i.e. gradient, length and percentage of vegetation cover) of degraded (i.e. with rills) and non-degraded roadcuts (i.e. without rills) and explored the relationship of the roadcut characteristics with the dimensions (widths and depths) of the rills. Degraded roadcuts were steep (52.21°), long (10.70 m), and had a low percentage of vegetation cover (24.12) when compared to non-degraded roadcuts which had a gradient of 28.24°, length of 6.38 m and 91.7% of vegetation cover. Moreover, the gradient and percentage of vegetation cover of the roadcut significantly determined the rill dimensions. The widths and depths of the rills increased with the increase in slope gradient and decreased with an increase in percentage of the vegetation cover. Moreover, the widths and depths of the rills decreased downslope of the roadcuts. Based on these results, re-vegetation of roadcuts as well as construction of gentle gradients could minimise rill erosion and hence the negative onsite and offsite effects.

Keywords: rill erosion; slope gradient, slope length; vegetation cover; roadcuts.

3.2 Introduction

Soil erosion is regarded as one of the most critical environmental problems worldwide (Meadows, 2003; Le Roux *et al.*, 2007; Wei *et al.*, 2007; Le Roux *et al.*, 2008; Schönbrodt-Stitt *et al.*, 2013; Ma *et al.*, 2014). It mainly occurs in the form of sheet, rill and/or gully erosion (Morgan, 2005; Le Roux *et al.*, 2008). Amongst the three forms, rill erosion remains the main cause for concern since it is a precursor of gully erosion. Rill erosion mainly occurs as a result of concentrated overland flow of water leading to the development of small well-defined channels (Haile and Fetene, 2012). These channels act as sediment sources and transport passages leading to soil loss (Wirtz *et al.*, 2012). Although soil erosion is a natural process, it has been accelerated by the human impact on the landscape due to agriculture, grazing, mining, and fire (García-Orenes *et al.*, 2009; Giménez-Morera *et al.*, 2010; Lieskovský and Kenderessy, 2012; Leh *et al.*, 2013; Mandal and Sharda, 2013; Zhao *et al.*, 2013; Ziadat and Taimeh, 2013). Roads, railways and other infrastructures also results in the soil degradation and changes in the landforms (Cerdà, 2007; Cao *et al.*, 2013; Cheng *et al.*, 2013; Jimenez *et al.*, 2013; Lee *et al.*, 2013; Villarreal *et al.*, 2014).

Construction of roads in South Africa, has resulted in the creation of roadcuts, some of which have developed extensive rills and fluting (or incipient gullies). Soil erosion on roadcuts is significant since soil loss can reach magnitudes of 247.6 t/ha/yr (Megahan *et al.*, 2001). Moreover, roadcuts have been regarded as the main source of erosion than other parts of the road system since they account for 70 to 90% of soil loss (Grace III, 2000). The off-site loss of sediment material may lead to river and reservoir siltation where sediment is deposited (Cerdà, 2007; Zhao *et al.*, 2013). This can exacerbate water management problems particularly in a semi-arid region such as South Africa, where water scarcity is frequent (Marker and Sidorchuk, 2003). Moreover, erosion on roadcuts may cause roadside slope instability (Osorio and De Ona, 2006; De Ona *et al.*, 2009). At present, large volume of soil is lost annually through water erosion in South Africa. It is estimated that South Africa losses approximately 400 million tons of soil per year, of which roadcut erosion is also a major contributor (Dlamini *et al.*, 2011). The economic costs associated with the negative impacts of erosion are significant. It is estimated that soil erosion costs approximately $ 200 million (US dollars) annually including the off-site costs of purification of silted dam water in South Africa (Le Roux *et al.*, 2008). Additionally, slope instability could create excessive maintenance costs (Robichaud *et al.*, 2001) and in extreme cases requires re-grading or reconstruction of the site (Persyn *et al.*, 2005). In the light of the above, understanding the relationship between the characteristics of roadcuts and the rill erosion can be important for environmentally sustainable future road construction and soil erosion control. The present study therefore aims to assess the characteristics (gradient, length, and vegetation cover) of degraded and non-degraded roadcuts and investigate the relationship between the characteristics of the roadcuts and the dimensions (width and depth) of the rills in the south-eastern region of South Africa.

3.3 Materials and Methods

3.3.1 Data Collection

3.3.1.1 Identification of Roadcuts

Roadcuts of interest were identified by first traversing main and regional roads in the south-eastern region of South Africa on Google Earth. Following the above procedure, field inspection was conducted on identified sites, to assess the actual condition of the roadcuts. Roadcuts were then numbered and random samples selected using random number tables, to get actual sizes for detailed investigation. The roadcuts were then categorised into degraded and non-degraded. For the purpose of this study, the degraded were those with the presence of either rills or flutes whereas non degraded roadcuts were those with no apparent rilling. This resulted in twenty nine degraded and twenty non-degraded roadcuts. The degraded roadcuts were further classified into three erosion categories based on the mean percentage cover of rills per square meter plots established on the roadcuts: (1) slight: less than 25% (2) moderate: between 25% and 50%; (3) extensive: between 50% and 75%; and (4) very extensive: above 75%. The selected roadcuts did not receive any form of treatment after construction (e.g. hydroseeding etc.) and were characterised by herbaceous vegetation cover. Additionally, the selected roadcuts were located along roads that were constructed at the same period to minimise the effects of the roadcuts age on erosion.

3.3.1.2 Measurement of the characteristics of roadcuts

The gradient, length, and percentage of vegetation cover were measured on the degraded and non-degraded roadcuts identified in the south-eastern region of South Africa. Slope profile measurements were done along three cross-profile transects on each roadcut by using an abney level, ranging rod and a measuring tape. Transects were established from the top to the bottom of the roadcuts, with the first transect running along the maximum slope length. The next two transects were located on both sides of the first transect and halfway to the end of the roadcut width (Figure 3.1). Slope profiles were measured by recording a series of measured lengths along a transect and corresponding series of measured angles. The slope gradient for each roadcut was calculated as the average of averages for each transect while the length was calculated by averaging the three transects.

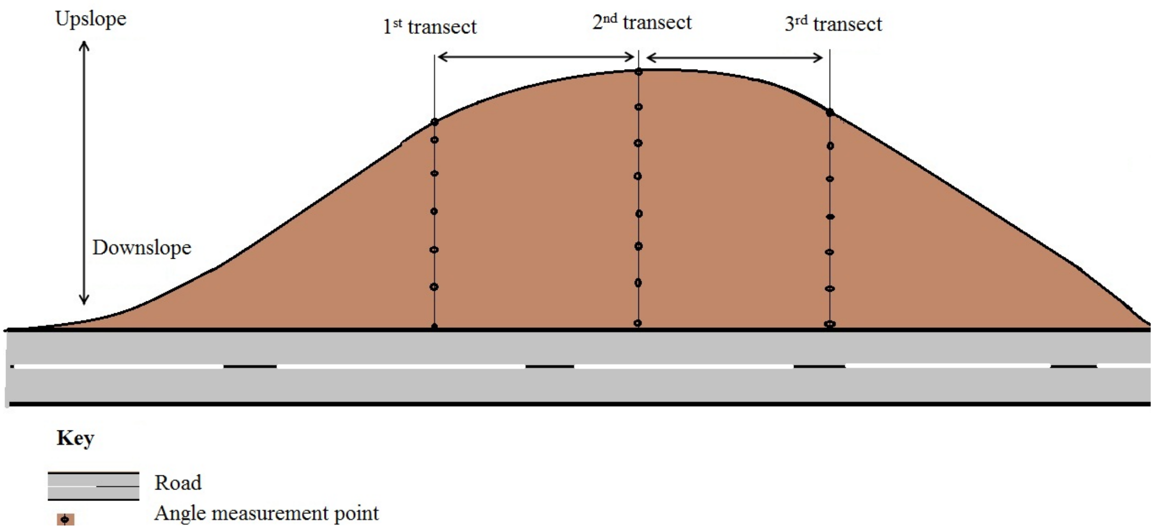

Figure 3. 1: Schematic representation of slope angle and length measurements on the roadcuts.

Percentage of vegetation cover was measured by demarcating transects made of 1 m long and 4 m wide plots which were then numbered. Random samples were selected from the numbered plots using random number tables, to get actual sizes for detailed investigation. This resulted in selection of more than 70 percent of the plots on each roadcut, of which the number of plots on each roadcut was determined by the surface area. In each plot, a 4 m string attached to two metal pins was placed at 0.5 m width of a plot. Vegetation cover was calculated as the total vegetated distance of the string to the total length of the string, and recorded as a percentage (Kercher *et al.*, 2003). Total percentage of vegetation cover for the entire roadcut was then calculated as the mean of all plots percentage covers (Bochet and García-Fayos, 2004).

3.3.1.3 The measurement of rill dimensions

Measurements of rill dimensions were made from 4 m^2 plots located upslope, midslope and downslope of the roadcuts (Figure 3.2). The widths and depths of the rill were measured at regular intervals (i.e. 0.01 m) along the sinuous length of the rill and the averages calculated (Hagmann, 1996; Sidle *et al.*, 2004).

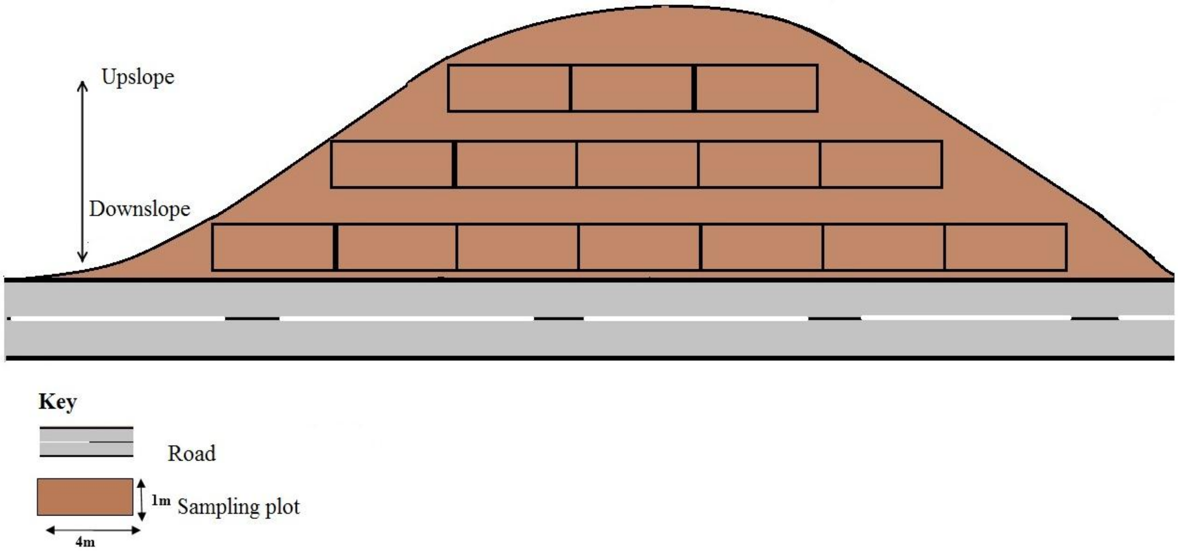

Figure 3. 2: Schematic representation of rill survey plots on the roadcuts.

3.3.2 Data analysis

Statistical analysis was performed using Statistical package for Social Sciences (SPSS) version 21 software. The Kolmogorov – Smirnof test was used to test data normality. A test of proportions was employed to determine whether there were significant differences between slope characteristics of the degraded and non-degraded roadcuts. One-way analysis of variance (ANOVA) at 95% confidence levels ($P < 0.05$) was used to determine whether there were significant differences between slope characteristics of the slightly, moderately, extensively and very extensively degraded roadcuts. Pearson correlation was used to evaluate whether there were any associations between slope characteristics and rill dimensions.

Similarly, one way ANOVA (P < 0.05) with a Turkey's HSD post hoc test was used to determine if there were any significant differences of rill dimensions upslope, midslope and downslope of the roadcuts.

3.4 Results

3.4.1 Characteristics of the roadcuts

The slope characteristics of the roadcuts are presented in Table 3.1. Results show that these characteristics ranged widely for the roadcuts. It can be observed that the mean slope gradient of the degraded roadcuts was higher (52.5°) than that of the non-degraded roadcuts (28.2°). Similarly, the mean length of degraded roadcuts was higher (10.7 m) when compared to that of the non-degraded roadcuts (6.4 m). The vegetation cover for degraded roadcuts was low, with a mean percentage of 24.1 while non-degraded roadcuts had higher mean percentage of vegetation cover of 91.7.

Table 3. 1: Descriptive statistics for slope characteristics.

	Degraded roadcuts				Non-degraded roadcuts			
Slope characteristics	min	max	mean	StdDv	min	max	mean	StdDv
Gradient (°)	24.5	78.3	52.5	13.1	13.2	42.9	28.2	9.5
Length (m)	5.1	20.0	10.7	4.0	5.7	14.0	6.4	3.3
Veg. cover (%)	0.0	45.5	24.1	24.5	50.42	100.0	91.7	14.0

*n = 29 degraded and n = 20 non-degraded

The results in Figure 3.3 show the significant differences of slope gradient, length and percentage of the vegetation cover between non-degraded (ND) and degraded (D) roadcuts. It can be observed that the slope gradient and length of degraded roadcuts are significantly ($p < 0.05$) higher than for non-degraded roadcuts. Moreover, vegetation cover for degraded roadcuts is significantly lower than that for non-degraded roadcuts.

The proportions for slope length and gradient on degraded roadcuts were also significantly higher than for non-degraded. It was noted that degraded roadcuts had significantly lower percentage of the vegetation cover. On the other hand, the results of ANOVA with post hoc test, showed that there are no significant differences ($p > 0.05$) amongst the site variables (slope length, gradient and percentage of the vegetation cover) of the slightly, moderately, extensively and very extensively degraded roadcuts.

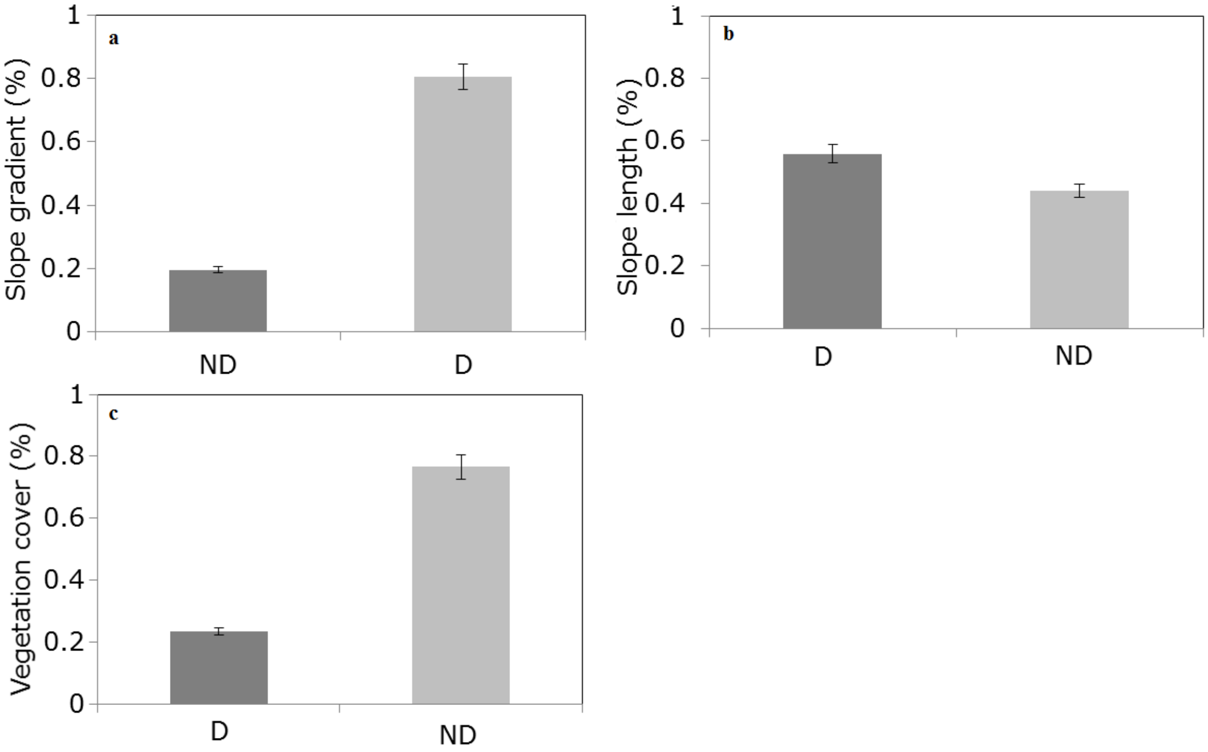

Figure 3. 3: Proportions of slope (a) gradient, (b) length, and (c) vegetation cover for non-degraded (ND) and degraded (D) roadcuts. Bars represent percentages, and whiskers represent 95% confidence intervals.

3.4.2 Rill dimensions

The results show that the characteristics of the roadcuts significantly determine rill dimensions (Table 3.2). Significant moderate positive correlations of gradient with both rill width and depth were observed, while percentage of the vegetation cover had a strong significant negative correlation with rill depth and width. The rill width and depth, however, were not significantly influenced by the roadcut length.

Table 3. 2: Pearson Correlation results between slope characteristics, rill width and depth

		Slope length	Slope gradient	Percentage of the vegetation cover
Rill width	Pearson correlation	0.21	0.37	-0.62
	Significance	0.19	0.02*	0.00*
Rill depth	Pearson correlation	0.22	0.34	-0.64
	Significance	0.11	0.03*	0.00*

Note: * Correlation is significant at 0.05 level.

The mean values for rill dimensions at different roadcut slope positions (upslope, midslope and downslope) are shown in Table 3.3.

Table 3. 3: Mean rill width and depth at different slope positions on roadcuts

Slope position	Width (m)	Depth (m)
Upslope	0.14	0.08
Midslope	0.11	0.06
Downslope	0.08	0.05

The rill dimensions were significantly different at different plot positions (Table 3.4), with values decreasing downslope. The results showed that the rill dimensions had highly significant differences between the upslope and downslope positions.

Table 3. 4: The results of ANOVA using a Turkey's honest significant difference post hoc test for rill dimensions (width and depth) and different slope positions (upslope, midslope and downslope) at 95% confidence level ($P < 0.05$)

Slope position	Rill width	Rill depth
US vs MS	0.15	0.10
US vs DS	0.00*	0.00*
MS vs DS	0.02*	0.04*

Note: US = Upslope; MS = Midslope; DS = Downslope; * Significant at 0.05 level

3.5 Discussions

This study aimed at evaluating the characteristics of the degraded and non-degraded roadcuts as well as assessing the relationship between the rill dimensions and the roadcut characteristics.

3.5.1 The characteristics of the roadcuts in terms of erosion

The results of this study have shown that the characteristics of the degraded roadcuts were significantly different from those of the non-degraded. For instance, it was noted that degraded roadcuts were characterised by high slope gradients and lengths, and low vegetation cover when compared to the non-degraded roadcuts. These results are in comparable with previous studies which indicated that these conditions increase the vulnerability of roadcuts to erosion (Flanagan *et al.*, 2002; Arnáez *et al.*, 2004; Bochet and García-Fayos, 2004). This is true because literature shows that an increase in slope gradient reduces the infiltration rate (Cerdà, 2007) hence increasing runoff (Megahan *et al.*, 2001; Arnáez *et al.*, 2004; Manyatsi and Ntshangase, 2008). A study by Arnáez *et al.* (2004) has demonstrated a significant positive relationship ($r = 0.76$; $p = 0.004$) between roadcuts slope gradient and runoff which could result in a substantial increase in the formation of rills (Fox and Bryan, 2000). Formation of rills results from the increased scouring capacity of concentrated runoff (Haile and Fetene, 2012).

Morover, degraded roadcuts, due to their long lengths when compared to the non-degraded suggest that they had more ability to increase runoff velocity resulting in both increased soil particle detachment and transport efficiency downslope (Chaplot and Le Bissonnais, 2003). The work of Kinnell (2000) has shown that an increase in slope length increases erosion by water, particularly when slope gradients exceed 10%. However, these findings are in contrast with other studies. For instance, Megahan *et al.* (2001) concluded that slope length alone or in interaction with other variables has no detectable effects on roadcut erosion. Similarly, Luce and Black (1999) found that roadcut slope length is insignificant in determining erosion by water.

The mean percentage of vegetation cover (predominantly herbaceous) for non-degraded roadcuts was high (91.7%) when compared to degraded roadcuts (24.12%), hence limited soil erosion was noted. This observation stands because vegetation cover has been found to stabilise and protect slopes against erosion since the roots hold soil particles together (Bochet and García-Fayos, 2004; Mohammad and Adam, 2010). Also, this can be explained by the ability of vegetation cover to moderate and dissipate the energy exerted by water (Lal, 2001; Ande *et al.*, 2009). In fact, vegetation intercepts rainfall, increases infiltration of water, intercepts runoff, and stabilizes the soil with roots (Loch, 2000; Bochet and García-Fayos, 2004). The results of this study are supported by the work of Cerdan *et al.* (2002) who observed that the occurrence of rill erosion on fields was directly a function of vegetation cover. Similarly, Arnáez *et al.* (2004) found a negative correlation (r = 0.60, p = 0.05) between vegetation cover and runoff. According to Jimenez *et al.* (2013), vegetation cover (i.e. herbaceous plants) protects the soil because of their high basal cover, dense and very fine root systems that bind the soil.

3.5.2 The relationship between slope characteristics and rill geometry

The roadcuts slope characteristics were assessed for their correlation with the rill dimensions. The results indicate that vegetation cover was the foremost significant variable in determining rill dimensions on the roadcuts, while slope length had no significant effect. A strong negative correlation between vegetation cover and rill dimensions suggests that an increase in vegetation cover reduces the cross sections of the rills. Vegetation cover in a rill catchment reduces runoff and sediment yield through rainfall interception, infiltration and resistance to flow (Woo *et al.*, 1997). A significant positive correlation of slope gradient and rill dimensions indicate that an increase in slope gradient increases the volume of rills and hence the volume of soil loss (Berger *et al.*, 2010). However, a moderate correlation of slope gradient and rill dimensions suggests that rill configuration is complex than merely slope gradient dependent.

The dimensions of rills that extended continuously from the top to the bottom of the roadcuts changed significantly downslope. Previous research indicated that significant changes in rill dimensions are determined by soil detachment and deposition along the length of the rill (Lei and Nearing, 1998; Bennett *et al.*, 2000). In this study, a decrease in rill depth downslope suggests that a progressive increase in sediment load downslope decreases detachment rate (Lei and Nearing, 1998). However, this was significant between upslope and downslope position, and between midslope and downslope positions. This suggests that detachment is active between upslope and midslope, while downslope positions are efficient in transporting the eroded sediment. The results are comparable with other studies available in the literature (Cochrane and Flanagan, 1997; Bennett *et al.*, 2000; Lei *et al.*, 2001; Merten *et al.*, 2001). Cochrane and Flanagan (1997) found that detachment decreases with the introduction of sediment at the top of the rill. Additionally, Bennett *et al.* (2000) observed that bed degradation was high in the upslope section of the channel while Merten *et al.* (2001) reported a decrease in detachment with an increase with sediment load along the channel length due to the suspended and bed load that reduced the detachment capacity. In this study, a decrease in rill width downslope implies that the scouring of the rill side walls decreased as a result of the limited scouring capacity of flow due to increase in the sediment load downslope (Bewket and Sterk, 2003). In addition, Lei *et al.* (2001) indicated that sediment load decreases the detachment rates particularly on slopes greater than 15^o. However, the findings of this study are in contrast with the study by Okoba and Sterk (2006) who observed a consistent increase in rill width and depth downslope and attributed this to cumulative runoff volume and velocity along the slope.

3.6 Conclusion

This study aimed to assess the characteristics (gradient, length, and vegetation cover) of degraded and non-degraded roadcuts and investigate the relationship between the characteristics of the roadcuts and the dimensions (width and depth) of the rills in the south-eastern region of South Africa. Degraded roadcuts were steeper, longer and had a lower percentage of vegetation cover when compared to non-degraded roadcuts. The results have shown that the widths and depths of the rills increase with an increase in slope gradient and a decrease in percentage of vegetation cover. Hence, low gradient and establishment of vegetation on roadcuts is recommended. Overall, while this study has contributed to the understanding of the relationship between the characteristics of the roadcuts and rill erosion, explicit investigations are required that would help maximise the quality of observations. Future research should focus on the measurement of the actual soil loss from the rills and the contribution of bulldozer teeth impressions on roadcuts, on the development of rills. Additionally, repeated observations should be made for an accurate description of rill evolution and to determine any significant change in the rill cross-sections. The results of this study can help road construction planners, engineers and site constructors to design roadcuts that are less vulnerable to erosion. Additionally, they could help Transport Department and road maintenance agencies in planning for roadcuts rehabilitation work.

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CHAPTER FOUR

EVALUATING SOIL LOSS ON ROADCUTS USING RILL DIMENSIONS AND SOIL PROPERTIES

This chapter is based on:

Seutloali, K. E. and Beckedahl, H. R., (In Review), “Evaluating soil loss on roadcuts in south-eastern South Africa using rill dimensions and soil properties”, *Journal of geographical sciences*.

4.1 Abstract

Evaluation of soil loss on roadcuts is critical for understanding soil erosion risk associated with roadcuts and hence the development of effective erosion control measures. This study assessed soil loss on roadcuts in the south-eastern region of South Africa using rill dimensions (i.e. width, depth and length) and investigated the relationship between soil loss and the soil properties which are: exchangeable sodium percentage, sodium adsorption ratio, organic carbon as well as percentage sand, silt and clay. Thirty roadcuts associated with rills were identified and the volume of rills, which is equivalent to the volume of soil loss was measured from 4m^2 plots located on the roadcuts. Soil samples from the sites were analysed in the laboratory for soil properties namely: exchangeable sodium percentage, sodium adsorption ratio, organic carbon as well as percentage sand, silt and clay. Statistical analysis showed that the volume of soil loss correlated significantly with all the rill dimensions, with rill depth ($r = 0.91$, $p < 0.05$) being the foremost variable in calculating rill volume than rill width ($r = 0.65$, $p < 0.05$) and length ($r = 0.88$, $p < 0.05$). Moreover, there were significant positive relationship ($p < 0.05$) between exchangeable sodium percentage ($R^2 = 0.65$), sodium adsorption ratio ($R^2 = 0.89$) and sand ($R^2 = 0.59$), and the volume of soil loss while organic carbon and percentage clay had a significantly negative relationship with the volume of soil loss with R^2 values of 0.37 and 0.51 respectively. The results underscore the usefulness of rill dimensions in quantifying soil loss on roadcuts. The results also indicate the significance of the roadcuts soil properties to soil loss.

Keywords: rill width, depth and length, soil loss, soil properties, soil erodibility

4.2 Introduction

It has been established that an increasing road network construction worldwide has resulted in creation of roadcuts that are susceptible to high rates of erosion and soil loss (Megahan *et al.*, 2001; Ramos-Scharron and Macdonald, 2007; Jordan and Martinez-Zavala, 2008). Roadcuts are recognised as the major source of erosion as they account for 70 to 90% of soil loss from the road system (Grace III, 2000). The steep slopes of the roadcuts result in reduced water infiltration that increases runoff accumulation (Arnáez *et al.*, 2004). Similarly, minimum vegetation cover increases runoff by decreasing water infiltration, and exposes the soil to easy soil detachment by raindrops (Jankauskas *et al.*, 2008).

Increased surface runoff flow generated on the roadcuts may travel downslope hence carrying away large quantities of soil and forming rills that can later become gullies (Persyn *et al.*, 2005). Continued soil erosion on roadcuts may contribute substantially to soil loss on the roadcuts and this may extend beyond the roadcut itself, but as far as degradation of water resources (Persyn *et al.*, 2005; Sheridan and Noske, 2007). Despite these negative impacts of erosion on roadcuts, an understanding of soil erosion related to roadcuts in South Africa is still rudimentary. Assessment of soil loss on roadcuts can be useful for understanding soil erosion risk and hence the development of effective erosion control measures (Xu *et al.*, 2006). Rill erosion has been shown to be the most predominant form of soil erosion by water that could provide an indication of soil loss (Melesse *et al.*, 2014). Therefore, measurement of rill erosion could provide a good understanding of soil loss due to erosion by water.

Rill cross-sections have been used to quantify soil loss on hillslopes and cultivated lands (Hagmann, 1996; Rejman and Brodowski, 2005; Okoba and Sterk, 2006). So far, to the best of our knowledge, no studies have been carried out yet to investigate soil loss on roadcuts utilising rill cross-sections. Rill survey approach could provide a good semi-quantitative information on soil erosion under field conditions in a fast manner, and does not involve costly instrumentation and sophisticated modeling (Bewket and Sterk, 2003). While the measurement of rill erosion would be an underestimation of actual soil loss because of exclusion of interrill erosion, the results of these measurements give the best approximation of erosion due to rills (Okoba and Sterk, 2006).

Several studies have evaluated soil loss on roadcuts with a view to understand the influence of slope gradient and length, rainfall characteristics as well as vegetation cover on erosion (e.g. Megahan *et al.*, 2001; Cerdà, 2007; Xu *et al.*, 2009). Evaluations of soil loss on roadcuts not only depend on these properties, which have been studied extensively, but also on the soil physical and chemical properties. It is perceived that soil properties determine the resistance of soil to concentrated flow which is an important factor in determining rill erosion (Knapen *et al.*, 2007). An understanding of the relationship between soil properties and soil loss on the roadcuts could help in coming up with better and effective soil erosion management strategies on roadcuts.

The aim of this study therefore, was to determine the volume of soil loss through rill erosion using the measured rill dimensions (i.e. length, width and depth) and investigate the relationship between the volume of soil loss and the soil properties which are: exchangeable sodium percentage (ESP), sodium adsorption ratio (SAR), organic carbon as well as percentage sand, silt and clay.

4.3 Materials and methods

4.3.1 Data collection

Roadcuts characterised by rills (n= 30) were selected along main roads found in the south-eastern South Africa. Rills were defined in this study as channels that are less than 0.5m wide. The presence of rills made these roadcuts ideal to investigate the volume of soil loss through rill erosion.

4.3.1.1 Field methods

Rill erosion measurements were carried out to assess the volume of soil loss from the roadcuts. A grid system of 1 m long and 4 m wide numbered plots was employed on the roadcuts for measurement of rill dimensions. The width of the plots ensured that each plot contained more than one rill. Random samples were selected from the numbered plots using random number tables, to get the actual number of plots for the measurement of rill lengths, widths and depths. The number of plots selected on each roadcut was determined by the surface area of the roadcut, but selection ensured that atleast more than 70 percent of the plots on each roadcuts were selected. A tape measure was used to measure the lengths and widths of the rills, while the rill depths were measured using a ruler. The widths and depths of the rills were measured at regular intervals along the sinuous length of the rill and averaged to give the mean width and depth of a rill. The volume of the rills was calculated in each plot using the measured rill dimensions (Hagmann, 1996; Sidle *et al.*, 2004). The cross-sectional area of the rill was calculated through approximation as either a rectangle (width x depth) or a triangle (1/2 horizontal width x depth). The volume of the soil lost from the rill was then calculated by multiplying the cross-sectional area by the length of the rill. The total volume of soil loss from rills in each plot was determined by summing the calculated volumes of the rills.

4.3.1.2 Soil analysis

Soil samples were obtained from the rill complex of the roadcuts and put in labelled sample bags. All sample bags were stored in dry conditions until they are transported to the laboratory for determination of the particle size distribution, organic matter, exchangeable sodium percentage (ESP), Sodium adsorption ratio (SAR). Soil texture (i.e. percentage sand, silt, and clay content) was determined by the pipette/hydrometer method for the fraction of particles with a diameter less than 2 µm (clay fraction) by sieving for particles between 200 and 2000 µm (coarse sand), and between 20 and 200 µm (fine sand), while the fraction between 2 and 20 µm (silt) was obtained by difference (Mesquita *et al.*, 2005). A portion of each sample was air-dried and sieved (0–2 mm) for soil organic carbon analysis, determined by the Walkley and Black method (Jordan and Martinez-Zavala, 2008). ESP and SAR was estimated from direct determination of exchangeable Sodium (Na), CEC, Calcium (Ca) and Magnesium (Mg). ESP and SAR were calculated in a similar manner as Makoi and Verplancke (2010) using the following equations:

$$ESP = \frac{Na\ exch}{CEC} \times 100 \qquad (1)$$

Where ESP is exchangeable sodium percentage, Na exch is exchangeable Sodium and CEC is cation exchange capacity.

$$SAR = \frac{\mathrm{Na}}{\frac{\sqrt{\mathrm{Ca}+\mathrm{Mg}}}{2}} \tag{2}$$

Where SAR is Sodium adsorption ratio, Ca is Calcium and Mg is Magnesium.

4.3.2 Statistical data analysis

Statistical correlations were performed to assess any associations between the individual rill dimensions and rill volumes. The Pearson's correlation was used on normally distributed variables while Spearman's correlation was used for non-normally distributed variables. The relationship between the volume of soil loss and the soil properties was determined by simple linear regression and the coefficient of determination (R^2) was reported. The coefficient of determination was selected in this study to assess the effects of each soil property on the volume of soil loss as well as how well each soil property explained the volume of soil loss. All computations were made using SPSS statistical package version 21.

4.4 Results

4.4.1 Characteristics of the rills

Table 4.1 shows the descriptive statistics of the rill characteristics for the roadcuts considered in this study. It can be observed that the mean rill depth was small (0.07) when compared to the mean width (0.17), with the mean width depth ratio of (2.1). The distribution of the rill dimensions across the studied roadcuts is shown in Figure 4.1. It can be observed that the rill lengths and widths were predominant in all size categories. However, the lowest size categories of the rill widths (0.01–0.09 m) were the most frequent, with the small proportions of percentage frequencies observed in higher class categories.

Table 4. 1: Descriptive statistics of measured rill dimension for 4m^2 plots on roadcuts

Variables	Range		Mean	StdDv
	Minimum	Maximum		
Length	0.12	1.00	0.60	0.30
Width (m)	0.01	0.39	0.17	0.12
Depth (m)	0.01	0.21	0.07	0.06
Width/Depth	0.88	9.77	2.10	1.58
Volume of Soil loss	0.00	0.40	0.15	0.12

* n=30

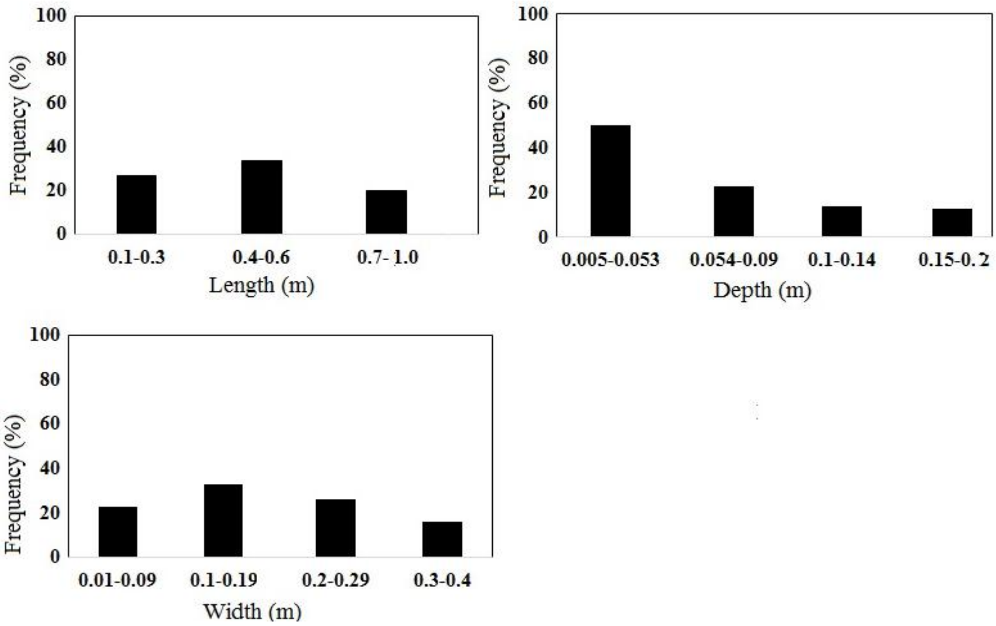

Figure 4. 1: Distribution of the sizes of rill dimensions across the studied roadcuts

The Pearson's and Spearman's correlation results for determining the relationship between the individual rill dimensions and rill volumes are given in Table 4.2. There were significant correlations ($p < 0.05$) between the volume of rills and all the individual rill dimensions.

Table 4. 2: Relationships between rill dimensions and the volume of rills from Pearson and Spearman correlation results

		Width	Depth	Length
Rill volume	Correlation	0.65	0.97	0.88
	Significance	0.00*	0.00*	0.00*

Note: * Correlation is significant at 0.05 level.

4.4.2 Soil properties and their relationship with the volume of soil loss

A summary of descriptive statistics for the measured soil properties is shown in Table 4.3. The mean sand content was high (49%) when compared to silt (21%) and clay (29%). The soil carbon content ranged from 0.1% – 0.5%, while ESP and SAR ranged from 1.0 – 11.3 and 1.3 – 15.3, respectively.

Table 4. 3: Descriptive statistics for the measured soil properties

Soil properties	Min	Max	Mean	StdDv
Sand (%)	6	84	49	26
Silt (%)	2	60	21	15
Clay (%)	6	70	29	23
Carbon (%)	0.101	0.567	0.348	0.132
ESP	1.027	11.265	6.201	2.952
ASR	1.325	15.257	6.651	4.261

Figure 4.2 shows the relationship between soil properties and the volume of soil loss. The results show that there is a significant positive relationship ($p < 0.05$) between exchangeable sodium percentage ($R^2 = 0.65$), sodium adsorption ratio ($R^2 = 0.89$) and sand ($R^2 = 0.59$), and the volume of soil loss. Moreover, organic carbon and percentage clay have a significantly negative relationship ($p < 0.05$) with the volume of soil loss with R^2 values of 0.37 and 0.51 respectively. Percentage of silt content however did not have any relationship with the volume of soil loss.

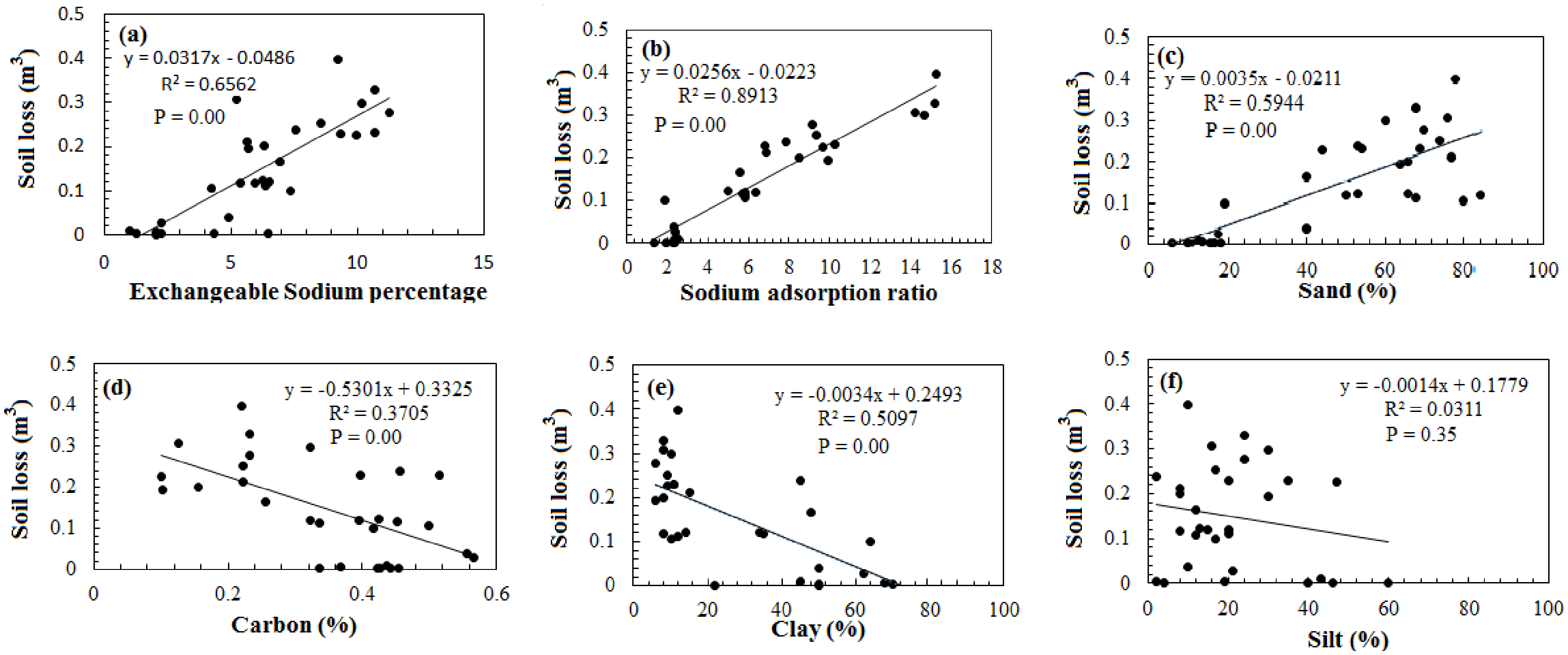

Figure 4. 2: Relationship between the volume of soil loss due to rill erosion and (a) exchangeable sodium percentage, (b) sodium adsorption ratio, (c) percentage sand, (d) Organic carbon percentage, (e) percentage clay, and (f) percentage silt.

4.5 Discussions

Evaluation of soil loss on roadcuts is critical for better understanding of the factors affecting the volume of soil loss and hence formulation of appropriate erosion control strategies on existing roadcuts as well as informed environmentally sustainable road construction. In this study the volume of soil loss through rill erosion on roadcuts was determined based on the measured rill dimensions namely (i.e. length, width and depth), and the relationship between the volume of soil loss and the soil properties which are: exchangeable sodium percentage (ESP), sodium adsorption ratio (SAR), organic carbon as well as percentage sand, silt and clay was investigated.

The results of this study showed that the volume of rills is positively and significantly correlated with individual rill dimensions, which could suggest that all the rill dimensions influence the volume of soil loss. These results therefore demonstrated rill dimensions as having the capability to provide a useful tool for estimating soil loss related to rill erosion. In this study, a remarkably high and significant coefficient obtained between rill depth and rill volume suggests a higher contribution of rill depth in calculating rill volume than rill width and length. However, this is in contrast with the results of Okoba and Sterk (2006) who noted a higher contribution of rill length in calculating the volume of rills. Moreover, the results of the current study showed that the rills were wider and shallow with width/depth ratio greater than one. Width/depth ratios greater than one often implies that the largest percentage of soil loss consists of fertile soil with high organic matter and this could result in reduced soil fertility (Øygarden, 2003).

The regression results showed that the soil properties linearly influence the volume of soil lost through rill erosion. The observed positive relationship between the volume of soil loss and ESP, SAR as well as percentage of sand content implied that soil loss due to rilling increased with an increase in ESP, ASR and sand content. The effects of ESP and SAR on soil erosion originate from their effect on clay dispersion (Igwe, 2001; Panayiotopoulos *et al.*, 2004). Clay dispersion involves the movement of clay particles to soil pores, resulting in a soil surface seal of lower permeability and increased runoff and soil loss (Flanagan *et al.*, 2002; Lado and Ben-Hur, 2004). Bagarello *et al.* (2006) found the highest decrease in hydraulic conductivity, and hence infiltration, ranging from 9-13% when SAR was zero, to 42-98% when SAR was increased to 30. This decrease in hydraulic conductivity was attributed to partial sealing of the soil pores by an increase in clay dispersion and mobilization due to increased SAR. Similarly, Tejada and Gonzalez (2006) found that an increase in ESP increases soil dispersability and disintegration of aggregates leading to higher soil loss. In contrast, Rienks *et al.* (2000) found no correlation between ESP and SAR and soil dispersion and concluded that although the soils may have high ESP and SAR, the low clay content may weaken the possible effects of ESP and SAR on dispersion. The results of the current study also show that an increase in sand content of the soil results in an increase in soil loss. Øygarden (2003) found severe erosion on soils with high sand content and this was attributed to less resistance of sand particles to erosion. Addisu (2009) stated that soils with high sand content tend to have low clay content and hence lower soil cohesive strength and more susceptibility to erosion by flowing water.

The observed negative relationship between percentage carbon and clay indicated the role of carbon and clay content in reducing soil loss. Organic carbon binds and bonds soil particles together, thereby reducing soil erodibility (Arthur *et al.*, 2012). Moreover, an increase in organic carbon results in increased infiltration rates (Pimentel, 2006). Similarly, clay content increases the aggregate stability thereby decreasing soil erodibility (Dlamini *et al.*, 2011). Haile and Fetene (2012) indicated that fine textured soils such as clays are not readily detached because of the strong cohesive forces that keep them aggregated. Yýlmaz *et al.* (2008) also observed a higher susceptibility of soil to erosion where the content of clay was low.

4.6 Conclusions

This study aimed to assess soil loss related to rill erosion by using rill widths, depths and lengths as well as to investigate the relationship between soil loss and the soil properties namely: exchangeable sodium percentage, sodium adsorption ratio, organic carbon as well as percentage sand, silt and clay on the roadcuts in the south-eastern region of South Africa. The results have shown that the rill dimensions provide free and readily available parameters that can be used to estimate soil loss on roadcuts. Moreover, the soil properties have a significant contribution and influence on the volume of soil loss on roadcuts along major armoured roads in the south-eastern region of South Africa. Percentage of silt content however did not show a significant relationship with the volume of soil loss.

Overall, this study has demonstrated the usefulness of rill dimensions in investigating soil loss on roadcuts in the south-eastern region of South Africa. Moreover, the results underscore the significance of exchangeable sodium percentage, sodium adsorption ratio, organic carbon as well as sand and clay contents in explaining the volume of soil loss on the roadcuts. Analysis of soil properties is recommended before roadcut construction activities as well as for implementation of appropriate erosion control measures that could reduce soil loss.

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CHAPTER FIVE

AN ASSESSMENT OF GULLY EROSION ALONG MAJOR ARMOURED-ROADS: A GIS AND REMOTE SENSING APPROACH

This chapter is based on:

Seutloali, K. E., Beckedahl, H. R., Dube, T. and Sibanda, M. (In Revision) "An assessment of gully erosion along major armoured-roads in south-eastern region of South Africa: A GIS and remote sensing approach", *Geocarto International*.

5.1 Abstract

An assessment of gully erosion along road drainage-release sites is critical for understanding the contribution of roads in soil loss and for informed sustainable land management practices. Considering that road related gully erosion activities have traditionally been measured using field methods that are expensive, tedious, limited spatially and temporally, it is important to identify affordable, timely and robust methods that can be used to effectively map and estimate the volume of gullies along road networks. In this study, gullies along major roads in the south-eastern region of South Africa were identified from remotely sensed datasets and their volumes and hence the volume of soil loss were estimated in a Geographic Information Systems environment. Also, biophysical and climatic factors such as vegetation cover, the road contributing surface area, the gradient of the discharge hillslope and rainfall were identified and derived from remotely sensed datasets using Geographic Information Systems techniques to find out if they could explain the volume of gullies that existed in this area. The results of this study indicate that hillslope gradient ($R^2 = 0.69$, $\alpha = 0.00$) and road contributing surface area ($R^2 = 0.63$, $\alpha = 0.00$) have a strong influence on the volume of soil loss along major road in the south-eastern region of South Africa. However, factors such as vegetation cover ($R^2 = 0.52$ $\alpha = 0.00$) and rainfall ($R^2 = 0.41$ and $\alpha = 0.58$) have a moderately weaker influence on the overall soil loss. Overall, the findings of this study highlight the importance of using remote sensing and Geographic Information Systems technologies in investigating the occurrence of gully erosion along major roads where detailed field work remains a challenge due to cost and time constraints.

Keywords: Armoured roads, Digital Elevation Model, drainage discharge sites, soil loss; road drains; Geographic Information Systems and remote sensing

5.2 Introduction

Roads play an important role in changing the near-surface hydrologic response (Ziegler and Giambelluca, 1997) and this often provides a conducive platform for concentrated runoff critical for causing accelerated soil erosion (Megahan *et al.*, 2001; Arnáez *et al.*, 2004; Bochet and García-Fayos, 2004; Cerdà, 2007; Ramos-Scharron and Macdonald, 2007; Jordan and Martinez-Zavala, 2008; Xu *et al.*, 2009; Baird *et al.*, 2012). For instance, roads change the processes that regulate the storage and distribution of water on the landscape (Ziegler and Giambelluca, 1997; Ramos-Scharron and Macdonald, 2007). This is through the creation of relatively impermeable surfaces that increase the frequency and magnitude of overland flow as well as the construction of roadcuts which often intercept subsurface flows thereby contributing to high overland flows (Wemple and Jones, 2003; Sidle *et al.*, 2004; Borga *et al.*, 2005). In a study conducted in a *Pinus* plantation located in southeast of the Queensland coastal plain, Forsyth *et al.* (2006) demonstrated that runoff was consistently higher along gravelled roads when compared to ungravelled roads. The high runoff generation levels from gravelled road surfaces were attributed to compacted gravel foundation which provided an impervious barrier. On the other hand, Ziegler *et al.* (2000) examined surface runoff along a road section and other surfaces on agricultural fields in Thailand. Their results showed that the Hortonian overland flow generated within 45 minutes had a runoff coefficient of about 80 percent in *c.* 105mmh^{-1} simulations in contrast to greater rainfall depths required to initiate the Hortonian overland flow in agricultural fields. The runoff coefficient of these surfaces ranged from 0 – 20 percent (Ziegler *et al.*, 2000). Although these are not the case studies of armoured roads, the scenarios are similar since slope hydrology is altered resulting in concentrated runoff.

Previous studies have shown that accelerated soil erosion from armoured (i.e. tarred surfaces) and non-armoured roads (i.e. untarred surfaces) constitutes a critical component which contributes towards global soil loss and land degradation (Ziegler and Giambelluca, 1997; Croke and Hairsine, 2006). For instance, a study by Addisu (2009) found that concentrated road drainage resulted in the development of gullies that lead to soil loss ranging from 12,530 m^3 to 71,420 m^3. Moreover, the resultant gullies become a potential sediment delivery pathways to surrounding fluvial networks (Ramos-Scharron and Macdonald, 2007; Macdonald and Coe, 2008), causing severe water quality deterioration which in turn poses a serious threat to aquatic life (Ziegler and Giambelluca, 1997).

Although a number of studies have been conducted on road-related soil erosion, most of these raised concerns about the effects of road-related runoff and even investigated factors responsible for gully erosion initiation along the road networks, specifically at the road drainage discharge sites (Montgomery, 1994; Beckedahl and de Villiers, 2000; Croke and Mockler, 2001; Nyssen *et al.*, 2002; Wemple and Jones, 2003; Takken *et al.*, 2008b; Addisu, 2009). However, for a comprehensive understanding of soil erosion and to ensure environmentally sustainable land management practices at road drain discharge sites, accurate, regular mapping and quantification of gullies is a necessity. So far, previous studies have been using field surveys and visual assessments in order to understand the extent of gully erosion along road sides (Croke and Mockler, 2001; Nyssen *et al.*, 2002). However, the main challenge with applying the above-mentioned approaches in mapping gully erosion is that they are costly and require more time, besides being labour intensive and sometimes inaccurate and biased (Perroy *et al.*, 2010). In the light of this background, it is therefore important to identify affordable, timely and robust methods that can be effectively used to map and estimate the volume of gullies, which is equivalent to the volume of the soil lost, along major road networks in order to address road-related erosion challenges.

Current advances in remote sensing technology and Geographic Information Systems (GIS) offer a significant potential for timely investigation of road-related soil erosion over a large area especially in areas where intensive field work remains a challenge (Le Roux *et al.*, 2007). For instance, freely available remote sensing datasets such as Google Earth (GE) and moderately high resolution digital elevation models (DEM) coupled with advanced GIS facilities can enhance timely mapping and quantification of volumes of soil loss due to road-related soil erosion (De Jong *et al.*, 1999). Remote sensing datasets allow for the delineation and mapping of areas that have been affected by soil erosion (Frankl *et al.*, 2013b). Previous studies demonstrated the utility of remote sensing datasets in mapping the extent of gully erosion (McInnes *et al.*, 2011; Frankl *et al.*, 2013a). For example, McInnes *et al.* (2011) found that Google-Earth images permit the evaluation of gully extent over a large area in a reasonably short time with less cost. Similarly, Frankl *et al.* (2013a) mapped gully networks using Google-Earth images, with good spatial accuracy and limited cost. As such, remote sensing datasets have greatly assisted in simplifying fieldwork, and to some extent, even substituted it (Frankl *et al.*, 2013b).

This study therefore, investigates the feasibility of using free-and-readily available remotely sensed data and GIS technologies in identifying and assessing road-related gully erosion, as well as examines possible physical and climatic factors (i.e. road contributing surface area, hillslope gradient and rainfall) that contribute to roadsides gully erosion in the south-eastern region of South Africa.

5.3 Materials and Methods

5.3.1 Estimation of vegetation cover, gully volumes and road contributing areas

Drainage discharge sites associated with gullies were first identified in the field and their locations recorded using a Global Positioning System (GPS). Drainage discharge sites are areas where concentrated road runoff is directed from the road surface onto a hillside (Montgomery, 1994) either through a culvert or a mitre drain. Vegetation cover at discharge hillslopes was estimated by a line intercept method (Zhou *et al.*, 1998; Kercher *et al.*, 2003). This method was applied in 10 m^2 plots placed along transects. Two crossing 10 m measuring tapes were used in each plot and percentage vegetation cover was calculated by dividing the length where the tape intercepted with vegetation by the total length of the tape.

A sample of the identified gullies and road contributing areas were selected to measure their volumes and areas in the field. The dimensions of the gullies (i.e. length, width and depth) were measured using a surveyors tape and their volumes calculated from the measured dimensions (Jungerius *et al.*, 2002) (Figure 5.1). The road contributing areas (viz. the combination of the road segment length and width) were derived by measuring the contributing road length and width with a trundle wheel (Takken *et al.*, 2008a). A road segment length was defined as the length of road that drains to a specific culvert or mitre drain (Bowling and Lettenmaier, 2001) while a road width was the distance between the break from the roadcut or the road ditch to the road surface, to the break of slope from the road surface to the ditch or the fillslope (Fu *et al.*, 2009). The area was then derived by multiplying the length and the width of the road.

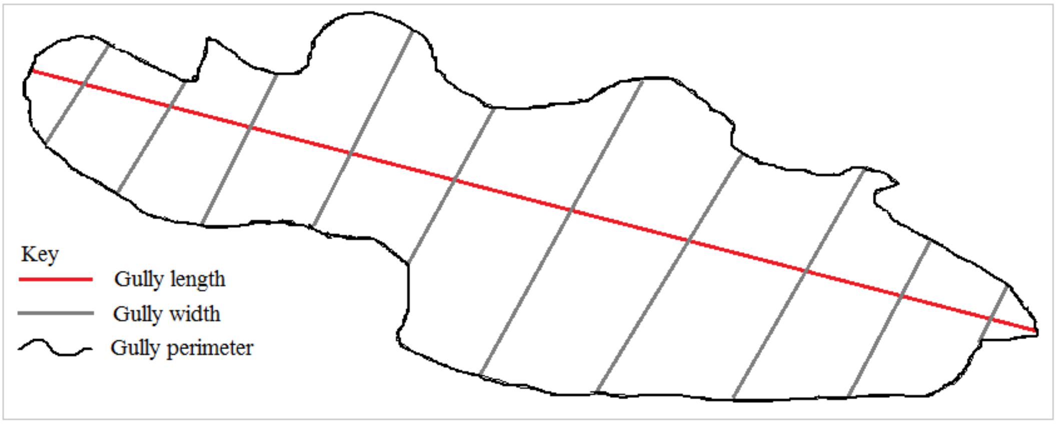

Figure 5. 1: Schematic illustration of gully length and width measurements in the field

A sample of 83 measured gullies and road contributing areas were also digitised from Google Earth image and saved as Keyhole Markup Language (KML) files and then converted into shapefiles to allow further pre-processing and analysis in a GIS environment. The areas of the selected gullies, and the road contributing surface areas were then computed in a GIS environment using spatial analyst tools. The volumes of gullies, which are equivalent to the volumes of soil lost, were estimated from the computed areas and measured depths (Wemple *et al.*, 2001; Jungerius *et al.*, 2002).

To validate the gully volumes and road contributing areas derived using remote sensing and GIS techniques, field measured gully volumes and road contributing surface areas corresponded with those obtained from Google Earth images hence the rest of the gullies and road contributing surface areas were digitised in Google Earth images and their volumes and areas computed as well in a GIS environment using spatial analyst tools.

5.3.2 The hillslope gradient

The gradient of the discharge hillslope was calculated from the free-and-readily available 30-m spatial resolution Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER) Global Digital Elevation Model (GDEM). The GDEM was acquired online from the web-link (http://gdem.ersdac.jspacesystems.or.jp/download.jsp). The Integrated Land and Water Information System (ILWIS), a remote sensing and GIS software, was used to process the DEM data of the study area. The hillslope gradients were calculated in ILWIS software using the following equation:

$$SLOPEPCT = 100 * HYP(DX,DY)/ PIXSIZE(DEM) \quad (1)$$

Where SLOPEPCT is the hillslope gradient in percentage, HYP is an in-built ILWIS function for computing slope, DX is height differences in X-direction, DY is height differences in Y-direction, and PIXSIZE(DEM) is the pixel size of the DEM. The hillslope gradient in percentage was then converted to degrees using the following equation:

$$SLOPEDEG = RADDEG(ATAN(SLOPEPCT/100)) \quad (2)$$

Where SLOPEDEG is the hillslope gradient in degrees, RADDEG is a function of converting radians to degrees and ATAN is a mathematical function used in the conversion process.

5.3.3 Rainfall data

The rainfall data of the area under study for the period 20 years (1994-2014) was obtained from the South African Weather Service and Institute for Soil, Climate and Water weather stations, through the Agro-Met data information system located at the Agricultural Research Council (http://www.arc.agric.za). The measured rainfall values from five closest rainfall stations to a location and a satellite rainfall estimation at that particular location are used in this method. Figure 5.2 shows rainfall distribution patterns across south-eastern South Africa.

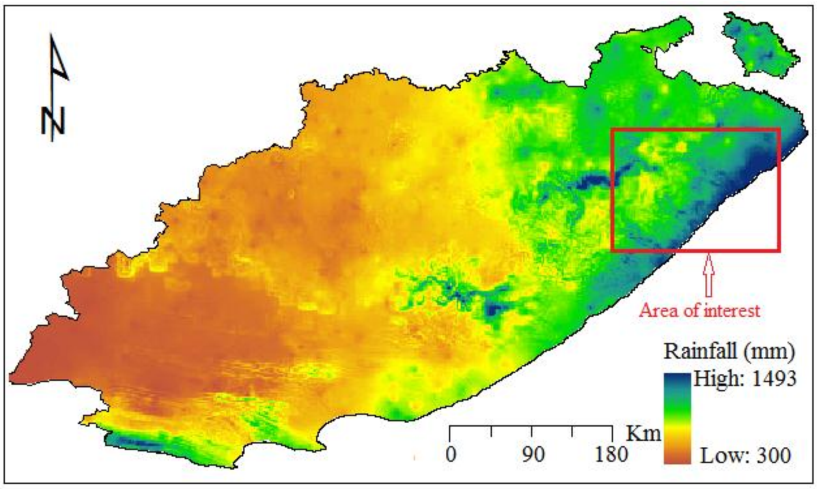

Figure 5. 2: Rainfall distribution map of the south eastern region of South Africa. The figure shows that there is significantly higher amount of rainfall towards the east, where the study was conducted. The approximate area of study is shown by the red box.

5.3.4 Soil

Soil data was derived from the Institute for Soil, Climate and Water (ISCW) of the Agricultural Research Council (ARC).

5.3.5 Determining conditions for soil erosion development

The gully sites and the selected biophysical and climatic factors were stacked in a GIS environment to assess the contributing factors towards the volumes of the gullies (Figure 5.3). To extract the biophysical and climatic factors of the mapped gullies, an overlay function in a GIS environment in the spatial analyst tools was used. Consequently, the extracted data for the biophysical and climatic factors of the mapped gullies was extracted as a table with the corresponding gully volumes. For further analysis, this data was then grouped based on the gully volumes, into 300m^3 categories. A 300m^3 interval was chosen for categorising the data after conducting exploratory analysis. The gully volumes were used as the grouping variable because there was no single variable that was hypothesised to be more responsible for gully erosion.

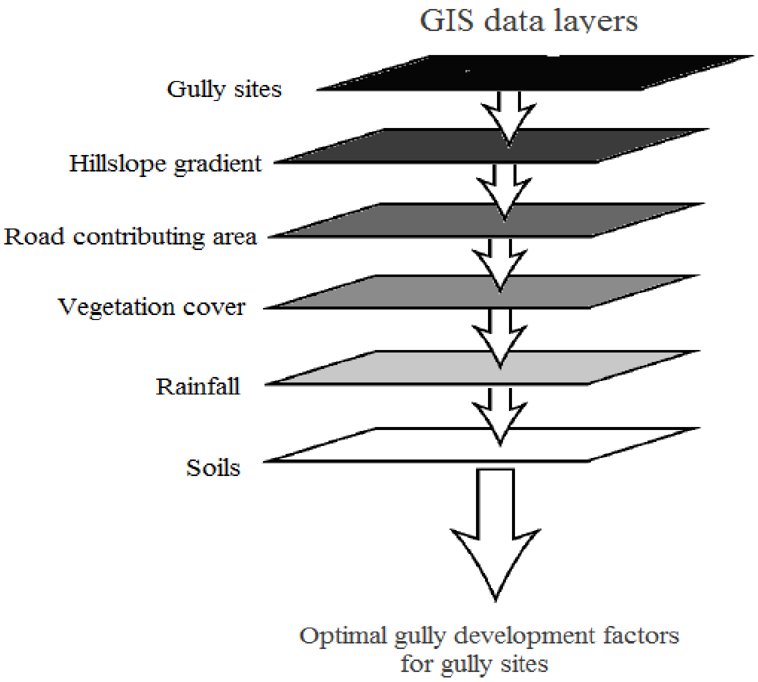

Figure 5. 3: Schematic representation of the methodological approach used to obtain biophysical and climatic data for different gully sites

5.4 Statistical analysis

The relationship between biophysical and climatic factors (i.e. hillslope gradient, vegetation cover, road contributing surface area and rainfall), and gully volumes was determined and evaluated using simple linear regression and the coefficient of determination (R^2) was reported. Further statistical analysis was performed to determine whether there were statistically significant differences ($\alpha = 0.05$) amongst the hillslope gradient, vegetation cover, road contributing surface areas and the volumes of gullies using one-way analysis of variance (ANOVA). Statistical analysis was implemented using SPSS version 21 software.

5.5 Results

5.5.1 Gully erosion related to road drainage outlets

Table 5.1 shows descriptive statistics for gully volumes and the possible factors of roadside gully formation (i.e. road contributing surface area, hillslope gradient, rainfall and vegetation cover). The results indicate that the road contributing area, gradient at the discharge hillslope and vegetation cover for the gully sites were significantly different (ANOVA; F_{82}=5.830, $p< 0.05$; F_{82}= 6.321, $p< 0.05$; F_{82}= 29.359, $p< 0.05$). It was however observed that the rainfall amount did not vary significantly across different gully sites.

Table 5. 1: Descriptive statistics for gully volumes and the possible factors of road drainage

	Minimum	Maximum	Average	Stdev.
Gully volume (m^3)	45.48	1046.89	65.35	16.42
Road contributing area (m^2)	133.19	2800.74	1173.95	639.69
Gradient (°)	4.74	27.39	15.10	5.52
Rainfall (mm)	570	945	738	100
Vegetation cover (%)	15.00	99.00	72.10	25.00

discharge hillslope gully formation

The results in table 2 show that higher gully volumes were associated with steeper hillslope gradients (greater than 9.87°), larger road contributing road areas (greater than 2147.58 m^2), and relatively lower vegetation cover (less than 39.61 %). These areas were also characterised by imperfect to poor drainage, low natural fertility, high erodibility, low base soil status that promotes increased gully development in these areas. On the other hand, it can be observed that areas with low gully volumes were associated with gentle hillslope gradients (less than 6^{o}), smaller road contributing areas (less than 140 m^{2}) and high vegetation cover (around 90 %). Also it can be observed that areas with less gully volumes were characterised by good drainage, moderately high erodibility and moderately high natural fertility.

Table 5. 2: Established biophysical and climatic conditions for gully sites.

Gully volume (m^3)	Number of gullies (%)	Road contributing area (m^2)	Slope gradient (°)	Rainfall (mm)	Vegetation cover (%)	Soil Characteristics
< 100	62	137.8	5.9	637	94.7	High base status, high soil depth, perfect to good drainage, low erodibility, moderate natural fertility
100 - 300	17	1437.1	7.7	713	73.4	Moderately restricted depth, moderately good drainage, moderately high erodibility
300 - 600	5	2147.6	9.9	792	66.8	Excessive drainage, high erodibility , low natural fertility poor drainage, wetness, high swell-shrink potential, plastic, sticky
> 600	16	2433.5	13.0	855	39.6	Excessive drainage, low natural fertility,imperfect to very poor drainage, excessive wetness, very high erodibility; poor water infiltration; seasonal wetness

5.5.2 The relationship between gully volumes and biophysical and climatic factors

The results in Table 5.3 and Figure 5.4 show the relationship between gully volumes and individual biophysical and climatic factors (i.e. road contributing area, hillslope gradient, vegetation cover, and rainfall). It can be noted that there is a linear relationship between gully volumes and most of the biophysical as well as climatic factors. For instance, a significant positive relationship ($R^2 = 0.63$, $\alpha = 0.00$), was found between the road contributing area and the gully volumes as well as between the hillslope gradient and the gully volumes ($R^2 = 0.69$, $\alpha = 0.00$). These suggest that the sizes of the gullies increased with increases in size of the road contributing areas and hillslope gradients. In addition, a negative relationship between the gully volumes and vegetation cover (R^2 value of 0.52 $\alpha < 0.05$) was established. It was observed that areas with vegetation cover around 90 % had low gully volumes of approximately less than 200 m^3 (see Figure 6d). Rainfall however, did not show a significant relationship with the gully volumes ($R^2 = 0.41$, $\alpha = 0.58$).

Table 5. 3: Regression analysis and ANOVA Turkey's honest significant difference post hoc test results showing the relationship between gully volumes and individual biophysical and climatic factors (i.e. road contributing area, hillslope gradient, vegetation cover, and rainfall)

	Coefficient of determination (R^2)	P-value
Road contributing area (m^2)	0.63	0.00 *
Hillslope gradient (^{o})	0.69	0.00 *
Rainfall (mm)	0.41	0.58
Vegetation cover (%)	0.52	0.00 *

Note: * Correlation is significant at 0.05 level.

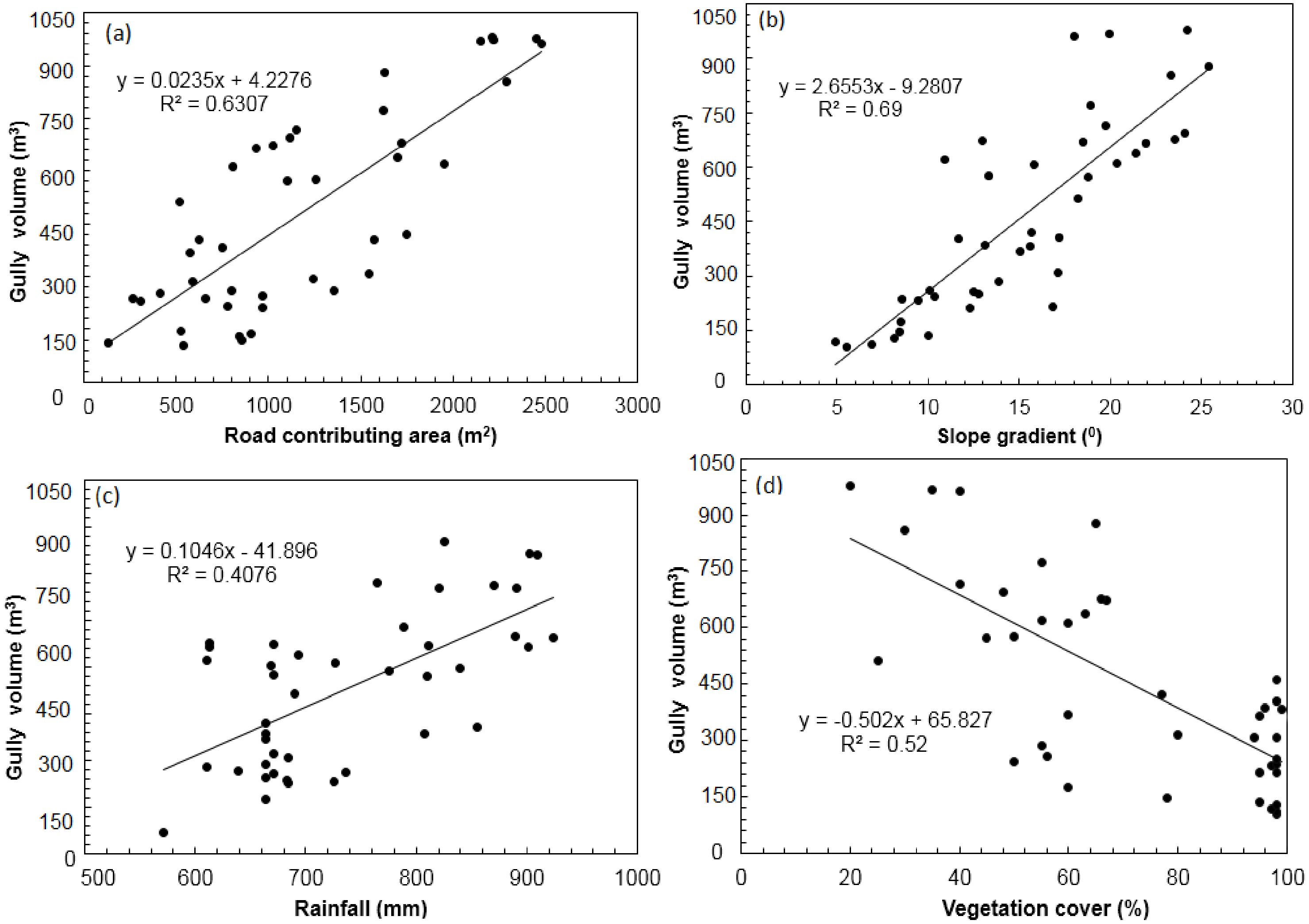

Figure 5. 4: The relationship between gully volumes and (a) road contributing area, (b) gradient, (c) rainfall and (d) vegetation cover of the road drainage discharge areas.

5.6 Discussion

The essence of this study was to generally provide a rapid method of mapping and quantifying the volume of road-related gullies based on the cutting edge satellite remote sensing and GIS technologies. A number of studies have been conducted to identify gully erosion and possible contributing biophysical and climatic factors using traditional methods (Jungerius *et al.,* 2002; Nyssen *et al.,* 2002). However, these methods are expensive, labour intensive and more importantly lack spatial representation, despite being regarded as accurate. In the present study, remotely sensed data and GIS technologies were used to map and quantify the volume of road-related gullies in the south-eastern region of South Africa.

This study identified gully erosion associated with concentrated road runoff discharged along main roads (i.e. armoured roads). It has been stated that roads contribute to the discharge of concentrated runoff onto the hillslopes through road drains, thus leading to the development of gullies along these areas. This can be explained by the fact that the road surfaces alter the hydrological functioning of hillslopes making a significant contribution to runoff. Specifically, roads create impervious surfaces that generate overland flow and allow rapid runoff (Croke and Hairsine, 2006). Also roadcuts intercept subsurface flow and then re-route it through overland flow (Ziegler *et al.*, 2000). This results in increased runoff concentration that creates the need for draining the road surface through mitre drains and culverts that result in gully erosion below the roadway. Gullies could be a sediment delivery pathway to stream channels particularly where the roads have been constructed upslope in areas where stream channels reside downslope (Croke and Mockler, 2001).

Regression analysis results indicated that the road contributing area, hillslope gradient and vegetation cover have statistically significant effects on the overall soil loss. From the results, an increase in the road contributing area promotes higher volumes of soil loss. This is because armoured road sections with larger road contributing areas generate larger volumes of runoff with high erosive power, capable of creating large gullies and vice versa (Fu *et al.*, 2009).The road contributing area, which is governed by road design and drain spacing along the road, determines the potential volume of runoff delivered to the drainage structure and hence released at the drainage outlet (Takken *et al.*, 2008a). For instance a study by Croke and Mockler (2001) demonstrated that a reduction of the road contributing area through a decrease in the drain spacing, could reduce gully erosion at drain release sites particularly where the discharge hillslopes are steep.

The hillslope gradient where concentrated road runoff is discharged also plays a critical role in determining gully erosion. In this study, a positive correlation was established between the volume of gullies and the hillslope gradient, implying that steeper hillslopes have a greater tendency to have more soil loss than gentle hillslopes. This is supported by the findings of Croke and Mockler (2001) who noted that 83 percent of the surveyed road relief culverts showed a full channel linkage, shown by a continuous gully development from the drain outlet to the stream, as compared to eight percent of mitre drains that showed evidence of full linkage. This was attributed to the discharge hillslope gradient of the relief culverts that was twice steeper than that of mitre drains. Similarly, Wemple *et al.* (1996) in their study found that the chances of gullying on steep slopes were significantly higher than on gentle hillslopes. This is because steep slopes do not allow more chance for runoff infiltration and hence the risk of gullying (La Marche and Lettenmaier, 2001).

The results of this study further demonstrated the importance of vegetation cover in controlling soil loss on the hillslope discharge areas. It was observed that the volume of gullies, and hence the volume of soil loss, decreased with an increase in vegetation cover. Much of the ability of vegetation cover in controlling gully retreat can be attributed to the presence of plant roots which have the capability to hold soil particles together. According to Valentin *et al.* (2005) plant roots reduce gully erosion by improving the structural stability and infiltration of the soil. The plant roots bind soil particles thereby forming mechanical barriers for soil and water movement (Bochet and García-Fayos, 2004), and provide a food source for microorganisms that form organic bindings that in turn increases soil stability and hence reduce soil erodibility (Gyssels and Poesen, 2003). Based on the findings of this study, it can be concluded that lack of, or limited vegetation cover facilitates further gullying and hence more soil loss on road drain discharge hillslopes.

The findings of this study have demonstrated that remote sensing and GIS technologies are useful tools that can aid in mapping and assessing road-related gully erosion as well as possible biophysical and climatic factors at interplay, especially in resource constrained regions (i.e. where detailed field work is difficult due to cost and time constraints) such as sub-Saharan Africa. Overall, the use of remote sensing has enhanced the identification, and mapping of areas affected by road-related gullies as well as the quantification of the total soil loss from these gullies. The successful performance of remotely sensed datasets can be associated with enhanced image spatial resolution that permits accurate identification, visualisation of the spatial distribution, navigation and delineation of areas affected by road-related gully erosion, a complex challenge when using traditional methods. Results of this study are consistent with those of Frankl *et al.* (2013b) who noted that gully networks in the May Ba'tati catchment, Northern Ethiopia could be effectively and accurately mapped using remotely sensed datasets such as Google Earth and GIS technologies. The increased potential of Google Earth for this geomorphological study was also increased by the ability to import digitised information into a GIS environment (Frankl *et al.*, 2013a) where geospatial data integration enabled further analysis of the road-related gullies. Similarly, Vrieling *et al.* (2007) noted that Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER) can accurately identify gullies over large areas. The current study differs from those mentioned above in the sense that the biophysical and climatic factors of the mapped gullies were also derived from remotely sensed datasets using GIS techniques to find out if they could explain the volume of road-related gullies.

5.7 Conclusion

This study aimed at investigating the feasibility of using free-and-readily available satellite remotely sensed dat and GIS technologies in mapping and assessing road-related gully erosion, as well as examining the possible physical and climatic factors (i.e. road contributing surface area, hillslope gradient and rainfall) that contribute to roadsides gully erosion in the south-eastern region of South Africa.

The results of this study have shown that:

1. Satellite remotely sensed data and GIS technologies provide a free, effective and timely means of obtaining useful information on the spatial distribution and extent of road-related soil erosion.
2. The road contributing surface area, vegetation cover and hillslope gradient have a significant contribution and influence on the volumes of the gullies along major armoured roads in the south-eastern region of South Africa.
3. Rainfall did not show a significant relationship with the gully volumes.

Overall, this research has demonstrated the usefulness of satellite remote sensing and GIS technologies in mapping and quantifying soil loss due to road-related gully erosion in the south-eastern region of South Africa. The findings of this research can probably help in guiding future studies in incorporating the use of GIS as a tool and remote sensing technologies when investigating road-related soil erosion at a regional scale especially in resources constrained Africa, where intensive and expensive field surveys are the only reliable methods.

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CHAPTER SIX

EVALUATING SOIL EROSION CONTROL METHODS ON ROADCUTS

This chapter is based on:

Seutloali, K. E. and Beckedahl, H. R., (In Review), "Evaluating soil erosion control methods on roadcuts in the south-eastern region of South Africa", *Journal of Geographical Sciences*.

6.1 Abstract

Soil erosion on roadcuts presents a great potential for detrimental environmental impacts due to soil loss. Controlling soil erosion is critical in minimising soil loss and the rehabilitation costs. Soil erosion control methods used on roadcuts in the south-eastern part of South Africa were identified and evaluated to assess their effectiveness. Twenty slope stabilizing methods and fifteen drainage control techniques were found and categorised (in terms of performance in controlling soil erosion) based on a scale of one, which means poor performance, to four depicting successful performance. The results of the study demonstrated that slope stabilisation methods were successful in controlling soil erosion. However, drainage control methods performed poorly. Slope stabilisation methods allowed vegetation re-establishment on the roadcuts, reducing direct rainfall impact and runoff. On the other hand, questionable performance of erosion control methods was attributed to a number of factors which include improper application, lack of inspection and maintenance, among others. Thus the study underscores the importance of proper application and monitoring of soil erosion control methods on roadcuts for effective soil erosion control.

Keywords**:** runoff, soil loss, slope stabilisation, drainage control, erosion control performance

6.2 Introduction

Soil erosion has become a major concern in both land and water resource management in South Africa (Le Roux *et al.*, 2008). Although soil erosion is a natural process, it is often accelerated by human activities such as road construction through alterations to slope gradient, removal of vegetation and damage to soil structure (Rickson, 2006). Roadcuts resulting from road construction present a potential for environmental degradation because sediment yields can reach magnitudes of 20 000 – 50 000 t/km^2/yr (Wolman and Schick, 1967). In fact, total soil loss generated from roadcuts are five to six times greater than roadbed and road fill embankments (Jordan and Martinez-Zavala, 2008). To add to this problem, the resulting soil loss has a potential to pollute water bodies (Lane and Sheridan, 2002; Sheridan and Noske, 2007) and cause slope instability (Osorio and De Ona, 2006). Pollution of water bodies due to sediment delivery, as well as slope instability can have devastating economic consequences if unchecked. For instance, increased turbidity as a result of sediment delivery to most of South African open water bodies and reservoirs has resulted in increased water treatment costs (Braune and Looser, 1989). It is estimated that high turbidity increases the annual water treatment in South Africa by R2Million (Braune and Looser, 1989). In addition, a number of slope failure incidences along South African roads have occurred over the past few years resulting in long and costly road closures; disrupting smooth traffic movements for prolonged periods (Leyland and Paige-Green, 2011). In the light of the above, effective soil erosion control measures are necessary for roadcuts, so that soil loss and the subsequent rehabilitation costs are minimised.

Soil erosion control techniques can reduce sediment yields from roadside slopes by approximately 60% (Grace III, 2000). Numerous studies have assessed the effectiveness of soil erosion control measures applied on roadside slopes (Grace III, 1999; Grace III, 2002; Benik *et al.*, 2003; Xu *et al.*, 2006; Jankauskas *et al.*, 2012). In a study conducted in North Alabama, Grace III (1999) found significant reductions in sediment yield and runoff on roadcut slopes and fill slopes with erosion control techniques (viz. native species grass, exotic species grass, and exotic species grass anchored with an erosion mat) as compared to the control (i.e. without erosion control techniques). Similarly, Grace III (2002) observed reductions greater than 70% of total soil losses on roadside slopes with erosion control treatments (viz. native species vegetation) while there was no reduction for bare soil control, in North Alabama. Additionally, in Minnesota, Benik *et al.* (2003) found a reduction in sediment yield and runoff on highway slopes with erosion control products which are: wood fibre blanket, straw/coconut blanket, straw blanket, bonded-fibre matrix and disk-anchored straw mulch as compared to bare slopes. Jankauskas *et al.* (2012) also observed a decrease of soil loss by 94.8 – 91.1% on a roadside slope with erosion control products (i.e. geotextile mats) in Luthiania.

While serious erosion of side slopes has been widely recognized and investigated, the investigations of erosion control measures are, in most cases, specific to non-engineering erosion control measures. To the best of our knowledge, no investigation into erosion control has been conducted on engineering erosion control measures. Engineering soil erosion control methods have been utilised on the roadcuts in the south-eastern parts of South Africa to reduce the erosion. To the best of our knowledge, the effectiveness of these methods has not been assessed, and their strengths and weakness are not documented. This study, therefore, aims to identify and evaluate the effectiveness of different soil erosion control methods on roadcuts found in the south-eastern part of South Africa as well as analyse the reasons for their success or failure and hence identify suitable erosion control strategies for artificial slopes of the cut-and-fill embankments.

6.3 Materials and Methods

6.3.1 Data collection and analysis

In order to identify soil erosion control methods (ECMS) employed on roadcuts, main roads in close proximity were traversed. Roads in close proximity were traversed to ensure homogeneity in terms of roadcuts age, geology and climate before selection of the study sites. The existing slope stabilisation and drainage control ECMs utilised on the roadcuts were noted, and this was followed by an allocation of unique numbers to the noted ECMs. The selection of ECMs for detailed investigation was based on the use of a random number table. The performance of ECMs was assessed semi-quantitatively by assigning scores from 1 (extremely poor) to 4 (very good) based on expert knowledge. Hence Table 6.1 shows the description of scores for assessing the performance of ECMs.

The scores were based on the ability of the ECMs to reduce soil erosion. According to (Ausilio *et al.*, 2001) slope stabilisation ECMs reduce the driving forces of slope failure and/or increase the resisting forces. Additionally, slope stabilisation structures should have facilities that allow plant growth (Department, 2005). Therefore, if the slope stabilisation ECM is not performing well, slope instability and erosion can be severe. On the other hand, ECMs for drainage of roadcuts are aimed at minimising the amount of water on the surface of the roadcut thereby reducing erosion potential (Harbor, 1999). Therefore, severe erosion in most instances occurs where drainage is not controlled through an area of ground disturbance (Claridge and Mirza, 1981). Uncontrolled erosion, in the long term, could induce slope failure (Sheridan and Noske, 2007; De Ona *et al.*, 2009). The analysis of the results of this study consisted of the general scores for all the ECMs evaluated.

Table 6. 1: Description of scores for evaluating the effectiveness of erosion control methods

ECM	Scores			
	1	2	3	4
Slope stabilisation	Slope failure	Rills and/or gullies and slope material slumping	No rills, gullies or slumping. Vegetation not reestablished	No erosion and vegetation well re-established.
Drainage control	Slope failure	Rills and/or soil pipes and/or gullies	No rills, soil pipes or gullies, but signs of severe sheet erosion	No signs of rills, soil pipes or gullies or soil pipes but minor sheet wash

Note: 1= very poor; 2= poor; 3= good; 4= excellent

6.4 Results

6.4.1 Performance of slope stabilisation methods for controlling erosion on roadcuts

Twenty slope stabilisation ECMs were identified along the traversed roads in the south-eastern parts of South Africa. In general, the performance of these ECMs was excellent (Figure 6.1). The highest proportion of ECMs (71.5%) obtained a score of 4 that shows an excellent performance. Additionally, 5.7% obtained a score of 3 which indicates a good performance. However, the lowest score of 1 that shows a very poor performance was obtained by 8.6% of the identified slope stabilisation ECMs while 14.3% obtained a score of 2 which shows a poor performance. The ECM scores were significantly different at 95%

confidence interval (Figure 6.2). This indicates that the performance of slope stabilisation ECMs varied from excellent to very poor.

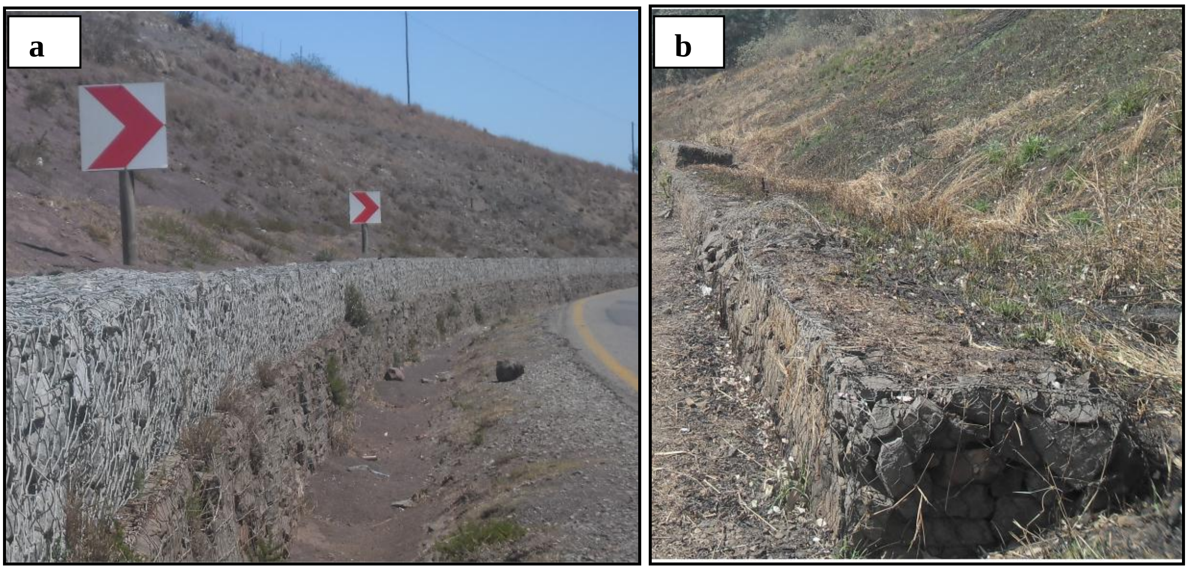

Figure 6. 1: Successful slope stabilisation erosion control methods of some of the roadcuts in the study region. The roadcuts are characterized by (a) vegetation regeneration and (b) fully established vegetation.

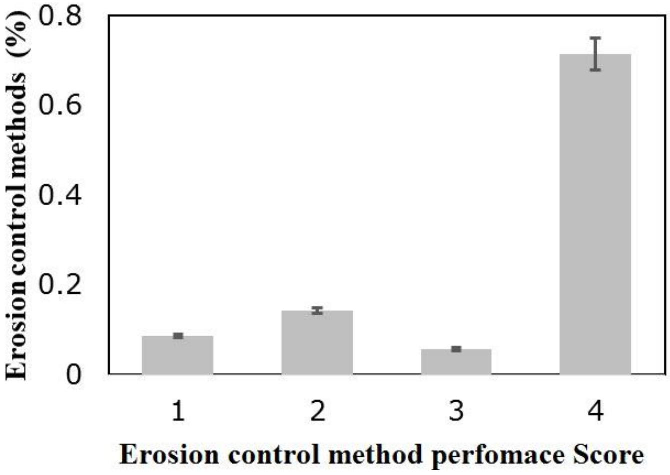

Figure 6. 2: Scores for the performance of roadcut stabilisation erosion control methods. Bars represent the percentages, and whiskers represent 95% confidence intervals.

6.4.2 Performance of drainage canals in controlling soil erosion on roadcuts

Fifteen drainage canals were identified along the traversed roads in the south-eastern part of South Africa. The general performance of these ECMs was poor (Figure 6.3). Figure 6.3a shows a roadcut with severe erosion and instability in the presence of a backslope drainage ditch. Similarly, Figure 6.3b depicts a roadcut with pipe erosion as a result of a failed backslope drainage.

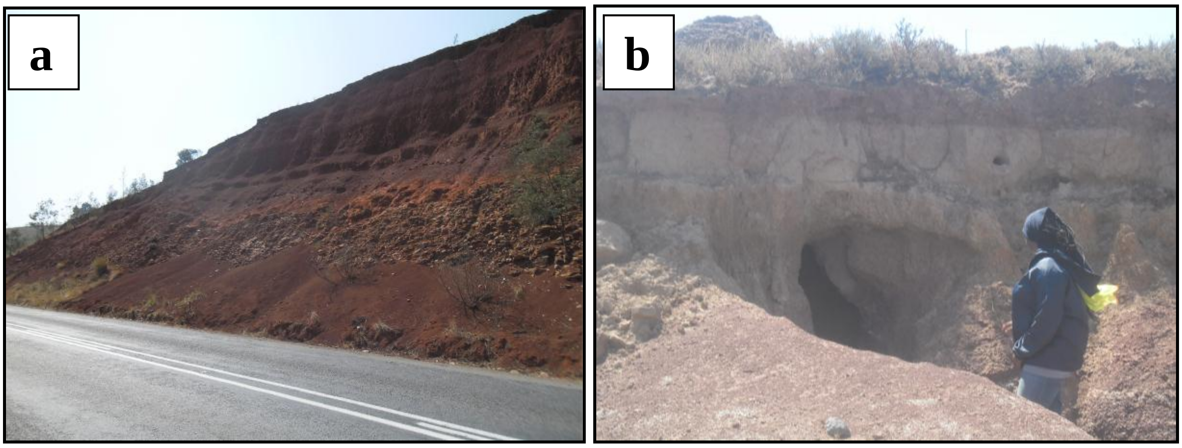

Figure 6. 3: Poor performance of some of the erosion control methods on the roadcuts in the study region. (a) An actively eroding roadcut with minor localised mass movement and sediment deposition at the toe of the slope. (b) Soil pipe on the roadcut due to a failed backslope drainage canal.

The highest proportion (46.2%) of the evaluated ECMs obtained a score of 1, indicating a very poor performance, while 38.4% obtained a score of 2 for poor performance. However, 15.4% obtained a score of 3 for good performance while none of the evaluated ECMs obtained a score of 4 for excellent performance. The scores of ECMs were significantly different ($p < 0.05$) suggesting that the drainage control ECMs on the roadcuts produced varied performances (Figure 6.4).

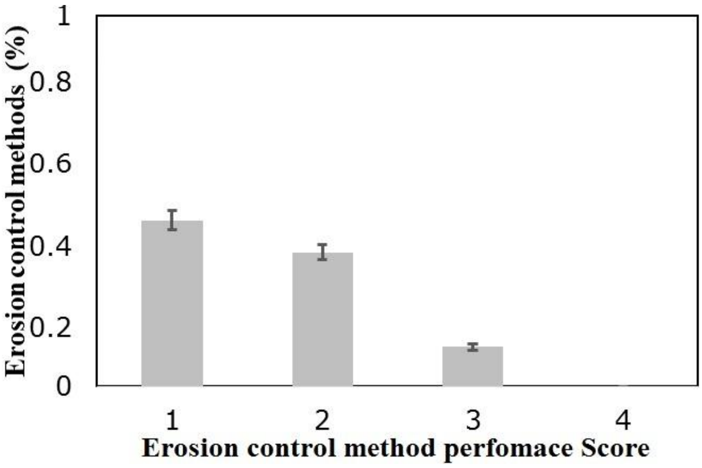

Figure 6. 4: Scores for performance of drainage canals. Bars represent the percentages, and whiskers represent 95% confidence intervals.

6.5 Discussion

This study identified and evaluated various soil erosion control methods used on roadcuts. The results indicate that slope stabilisation methods and slope drainage canals are the most popular methods used for controlling soil erosion on roadcuts in the south-eastern part of South Africa. Slope stabilisation soil erosion controlling measures seem to present a very good performance in minimising soil loss in roadcuts as compared to the drainage control ECMs. These results suggest that there are certain reasons for successes and failures of soil erosion control methods used on roadcuts as discussed in the sections below.

6.5.1 Performance of slope stabilisation erosion control methods

Slope stabilisation ECMs successfully controlled erosion on the roadcuts and allowed reestablishment of vegetation. This could be the result of their ability to increase resistance to the driving forces of erosion (Ausilio *et al.*, 2001). In addition, the enhanced erosion control success is likely to result from reestablishment of vegetation observed on the roadcuts. That revegetation is an effective erosion control technique has been reported by several studies (Benik *et al.*, 2003; Sanguankaeo *et al.*, 2003; Truong and Loch, 2004). This is because vegetation cover protects against erosion and stabilises the slopes as the roots hold soil particles together (Collison and Anderson, 1996; Bochet and García-Fayos, 2004). Furthermore, it intercepts rainfall and reduces runoff by increasing infiltration of water (Claridge and Mirza, 1981; Faucette *et al.*, 2006). Vegetation cover also moderates and dissipates the energy exerted by water (Lal, 2001; Ande *et al.*, 2009). Additionally, establishment of vegetation cover provides long term erosion control (Benik *et al.*, 2003) and improves the aesthetic value of the landscape (Montoro *et al.*, 2000). Consequently, vegetation cover re-established on the roadcuts ensured stabilisation and prevented soil erosion. While the highest number of ECMs prevented erosion and allowed vegetation regeneration, however a small proportion of slope stabilisation ECMs were not successful. This could be explained by the fact that some of these ECMs had recently been applied hence their performance not yet realised. Additionally, poor application of ECMs might have exacerbated their poor performance.

6.5.2 Performance of drainage canals in controlling soil erosion on roadcuts

Drainage canals were not successful in controlling erosion on the roadcuts. Although these drainage control ECMs are aimed at minimising the amount of water on the surface of the roadcut thereby reducing erosion potential (Harbor, 1999), the results of this study demonstrate that erosion occurred on the roadcuts with these ECMs. Despite the ability to restrict the amount of water flowing over the surface of the roadcuts, drainage control ECMs do not protect the surface of the roadcuts from erosion. Lack of protective layer on the roadcut allows easy soil detachment and transport due to lack of ground cover to protect soil from raindrop impact and concentrated overland flow (Claridge and Mirza, 1981). Hence erosion can still prevail even in the presence of a drainage canal. In order to ensure their effectiveness, drainage canals must be applied in conjunction with the protective layers on the surface of the embankments to protect the soil from the direct impact of rainfall and runoff. Protective layers such as erosion control blankets could reduce runoff and soil erosion by improving the soil quality (Bhattarai *et al.*, 2011) and enhancing vegetation (Faucette *et al.*, 2006) that would offer a permanent erosion control. Additionally, geotextiles could control rain splash and runoff (Bhattacharyya *et al.*, 2010) and promote a micro-climate for subsequent vegetation growth (Sutherland and Ziegler, 2006).

In addition to lack of protective layers to control erosion on the surface of the roadcuts, the poor performance of drainage control canals could have resulted from their poor application. For instance, pipe erosion was observed on a roadcut with a poorly constructed drainage canal (Figure 4a). The main purpose of the canal was to restrict the amount of water flowing over the surface of the roadcut through enhanced infiltration (Beckedahl and de Villiers, 2000). This canal however, resulted in soil piping due to increased water infiltration coupled with dispersive soils (Beckedahl and de Villiers, 2000). According to Beckedahl and de Villiers (2000) the reasons for this poor performance was the lack of consideration of the susceptibility of the soil to subsurface erosion. These findings highlight the importance of adequate provisions to reduce the adverse effects of drainage control ECMs and hence enhance soil erosion control performance. For instance, an effective mechanism to prevent piping is to establish drainage holes on the roadcut to allow groundwater to drain freely (Kotze, 2002). In addition, infiltration of water can be prevented by putting in place armoured drainage canals that diverts water away from the roadcut. As a standard soil erosion control mechanism, the area where the drainage canals discharge water is to be packed with pre-cast concrete grass blocks which, according to Schoof (1998) spread the water over a large area thereby preventing erosion. A successful performance of ECMs can further be enhanced by an understanding of erosion and sedimentation processes, as well as site realities that could assist in the development of practical and effective ECMs (Harbor, 1999). This can be achieved by the cooperation between engineers and soil erosion specialists.

Poor performance of ECMs was possibly further exacerbated by the lack of continuous inspection, reinforcement and repairs that undermined the designed purpose of the ECMs. In order to avoid these conditions, ECMs should be inspected on regular basis, repaired and replaced where damaged and protected from subsequent failure where erosion is occurring (Dias *et al.*, 2011). Additionally, Inspection is necessary to allow adjustments to the ECM to account for new or changing site conditions over time and correction of common installation errors (Harbor (1999).

Poor erosion control, in the long term, could lead to excessive erosion on the roadcuts and ultimately induce slope failure even in the presence of the ECMs. This in turn could lead to serious damages to the surrounding environment (Xu *et al.*, 2009). An ultimate, long term erosion control on roadcuts can be provided through formulation of legislative framework that stipulates standard specifications relating to soil erosion control (Kakembo, 2000) on roadcuts.

6.6 Conclusion

Soil erosion control methods employed on the roadcuts were identified and evaluated. Slope stabilisation erosion control methods seem to perform very well as noted by the regeneration of vegetation. However, drainage control methods did not successfully control erosion on the roadcuts and this was mainly attributed to their poor application. Furthermore, lack of inspection and maintenance of the existing erosion control structures undermined their ability to control erosion leading to poor performance. For an effective soil erosion control on the roadcuts, the results of this study suggest the use of erosion control methods that also facilitate vegetation reestablishment. It is also suggested that the application of erosion control methods should be carried out through the cooperation between engineers and soil erosion specialists to ensure proper application. Furthermore inspection and maintenance should be undertaken at regular basis to ensure proper functioning of the erosion control measures. Overall, the effectiveness of soil erosion control measures on roadcuts can be ensured though formulation and implementation of adequate legislation.

In the future, additional research is required to measure the actual soil erosion (i.e. sediment yield and runoff) in the presence and absence of erosion control methods in order to obtain quantitative data that would help in determining the amount of soil erosion reduced by erosion control measures. In addition, future research will identify the offsite effects related to poor erosion control on roadcuts in order to understand the possible negative environmental effects. Although the study did not aim at providing a method for quantifying the effectiveness of erosion control programs, it is however recommended that the strength and dependability of this method should be carried out for validation purposes.

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CHAPTER SEVEN

ROAD-RELATED SOIL EROSION IN CONTEXT: A SYNTHESIS

7.1 Introduction

Soil erosion related to roads is currently viewed as one of the serious causes of environmental degradation (Ramos-Scharron and Macdonald, 2007; Jordan and Martinez-Zavala, 2008). However, while several studies have investigated soil erosion related to unpaved roads in South Africa (Beckedahl *et al.*, 1998; Moodley *et al.*, 2011; Seutloali, 2011) and a few sought to understand accelerated soil erosion due to artificial road drainage (Beckedahl and de Villiers, 2000), so far, none has been carried out to fully understand the underlying determinants of soil erosion on roadcuts, evaluate soil loss related to rill erosion on roadcuts, and investigate the effectiveness of soil erosion control methods. Moreover methods such as remote sensing technologies have not been fully explored in terms of improving road-related erosion research. Road-related erosion, if not well investigated, understood and monitored, can in the long run lead to environmental challenges that could result in economic ramifications related to soil rehabilitation and water treatment in a region.

In an effort to minimise the potential negative impacts of road-related soil erosion in South Africa, an integrated management strategy is needed involving the evaluation of the determinants of erosion on roadcuts, assessment of soil loss due to erosion, evaluation of the effectiveness of soil erosion control methods, as well as exploration of the utility of remote sensing datasets in investigating erosion related to road drainage. Previous research has shown that roadcuts are the major contributors towards road-related soil erosion accounting for 70 to 90% of the total soil loss from the disturbed roadway area (Grace III, 2000). Hence, there is a need to investigate the determinants of erosion on roadcuts to guide environmentally sustainable future road construction. Moreover, a diversity of erosion control measures for controlling erosion on roadcuts need to be investigated in terms of their effectiveness, as well the identification of a method that is cost effective and operational across different landscapes. Additionally, while a variety of techniques are available to investigate road-related erosion (e.g. from field measurements to soil erosion prediction models) and could assist in understanding the nature and severity of road-related erosion as well as can help guide future development and erosion control efforts, there is a need for identification of methods that will bring into consideration the financial implications, real time detection and advanced techniques for monitoring road related soil erosion.

Hence the objectives of this study were:

1. To provide an overview of the effects of roads on soil erosion by water, and to understand the structural designs that facilitate these soil erosion processes as well as the different approaches that have been used to assess erosion.

2. To investigate the relationship between roadcut characteristics and the nature as well as extent of soil erosion.

3. To evaluate the volume of soil lost through erosion on the roadcuts by utilising a volumetric survey of rills.

4. To investigate the prevalence of gully erosion associated with concentrated runoff generated from the road surface at road drainage release sites using remotely sensed datasets.

5. To identify and evaluate the effectiveness of different soil erosion control methods.

6. To make recommendations as to the effective erosion control mechanisms for the environmentally sustainable construction and maintenance of primary road networks.

7.2 Evaluating the causal factors of rill erosion on roadcuts

An understanding of the determinants of soil erosion on roadcuts is essential for environmentally sustainable future road construction and soil erosion control. In this thesis, the characteristics (i.e. gradient, length, and vegetation cover) of degraded and non-degraded roadcuts were measured to investigate why certain roadcuts were eroded while others were not, and the relationship between the roadcut characteristics and the dimensions (width and depth) of the rills were evaluated (Chapter 3). The results show that the degraded roadcuts had significantly steep gradients (52.21°), long lengths (10.70 m) and low percentage of vegetation cover (24.12) when compared to the non-degraded roadcuts which had a mean gradient of 28.24°, length of 6.38 m and 91.7 percentage of vegetation cover. Figure 7.1 shows the significant differences of slope gradient, length and percentage of the vegetation cover between non-degraded (ND) and degraded (D).

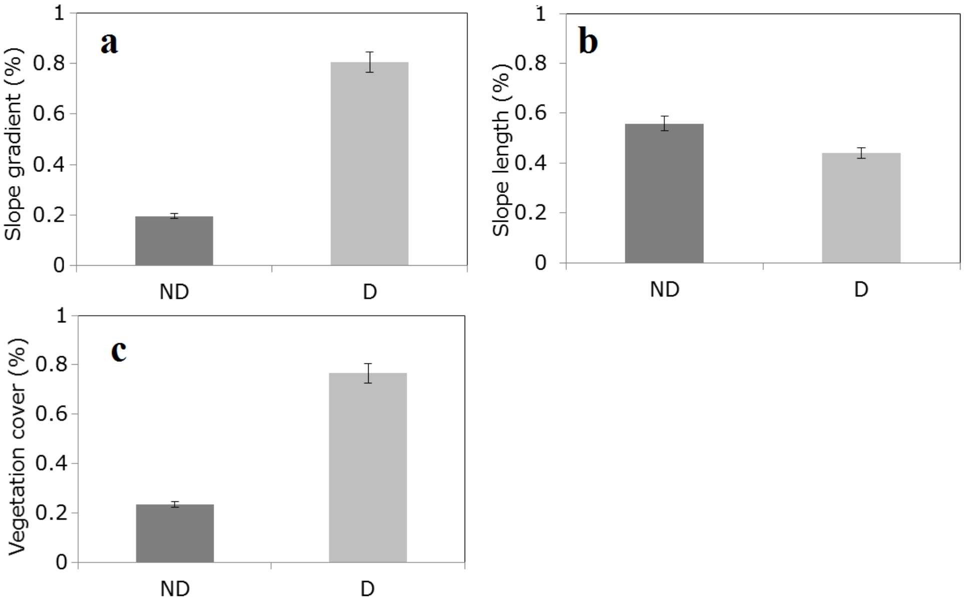

Figure 7. 1: Proportions of slope (a) gradient, (b) length, and (c) vegetation cover for non-degraded (ND) and degraded (D) roadcuts. Bars represent percentages, and whiskers represent 95% confidence intervals.

The results of the study further showed that the gradient and percentage of vegetation cover of the roadcuts significantly determine the rill dimensions (Table 7.1) with widths and depths of the rills increasing with the increase in slope gradient and decreasing with an increase in percentage of the vegetation cover.

Table 7. 1: Significant ($p < 0.05$) relationships between slope characteristics and rill width as well as depth from Pearson correlation results

		Slope length	Slope gradient	Percentage of the vegetation cover
Rill width	Pearson correlation	0.21	0.37	-0.62
	Significance	0.19	0.02*	0.00*
Rill depth	Pearson correlation	0.22	0.34	-0.64
	Significance	0.11	0.03*	0.00*

Note: * Correlation is significant at 0.05 level.

Since the results of the study indicated that there is a moderate positive relationship between the gradient of the roadcuts and rill sizes, and a moderate negative relationship with vegetation cover, the study further investigated the level of the relationship with the soil properties.

7.3 Soil loss associated with rill erosion and the influence of soil properties on the roadcuts

An evaluation of soil loss related to rill erosion on roadcuts is significant for understanding soil erosion risk and hence the development of effective erosion control (Xu *et al.*, 2006). The volume of soil loss through rill erosion was evaluated by using the measured rill dimensions (i.e. length, width and depth) and the relationship between the volume of soil loss and the soil properties which are: exchangeable sodium percentage (ESP), sodium adsorption ratio (SAR), organic carbon as well as percentage sand, silt and clay contents was investigated in this thesis (Chapter 4). The results showed that the mean rill depth was small (0.07 m) when compared to the mean width (0.17 m), with the mean width depth ratio of (2.1). The results of correlation analysis showed that there were significant correlations ($p < 0.05$) between the volume of rills and hence hence soil loss, and all the individual rill dimensions (i.e. depth, length and width) (Table 7.2). In addition there was a higher contribution of rill depth in calculating rill volume than rill width and length as shown by the correlation results.

Table 7. 2: Relationships between rill dimensions and the volume of rills from Pearson and Spearman correlation results

		Width	Depth	Length
Rill volume	Correlation	0.65	0.97	0.88
	Significance	0.00*	0.00*	0.00*

Note: * Correlation is significant at 0.05 level.

The regression results showed that the soil properties linearly influence the volume of soil loss through rill erosion (Figure 7.2). There was a positive relationship between the volume of soil loss and ESP, SAR as well as percentage of sand content. On the other hand, percentage carbon and clay content had negative relationships with volume of soil loss while percentage of silt content had no significant relationship.

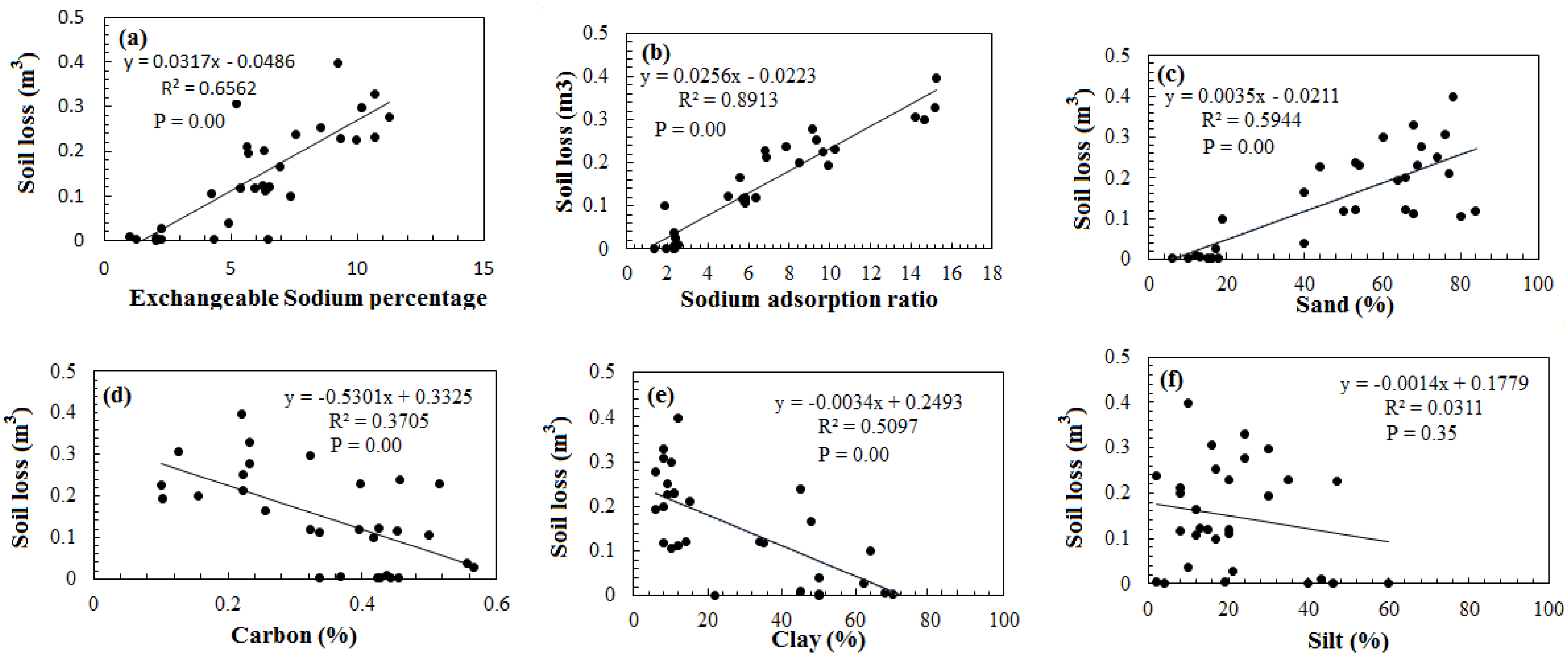

Figure 7. 2: Relationship between the volume of soil loss due to rill erosion and (a) exchangeable sodium percentage, (b) sodium adsorption ratio, (c) percentage sand, (d) Organic carbon percentage, (e) percentage clay, and (f) percentage silt.

The results demonstrated the significance of rill dimensions in investigating soil loss on roadcuts. However, field measurement of erosion features require more time and are labour intensive especially if applied at a large scale. Therefore, the potential use of remotely sensed datasets to evaluate road-related erosion was investigated.

7.4 Evaluating gully erosion associated with concentrated road drainage using a remote sensing approach

Having been able to investigate soil loss through field measurement of rill dimensions, the feasibility of using remotely sensed data and Geographic Information Systems (GIS) technologies to identify and assess road-related gully erosion was investigated (Chapter 5). Remote sensing technologies and GIS offer a potential for timely investigation of road-related soil erosion over a large area especially in areas where intensive field work remains a challenge (Le Roux *et al.*, 2007). There is increasing evidence that remote sensing datasets allow for the delineation and mapping of areas that have been affected by soil erosion (McInnes *et al.*, 2011; Frankl *et al.*, 2013). Moreover, digital elevation models coupled with GIS facilities can enhance extraction of topographic variables that influence erosion (Kakembo *et al.*, 2009).

In this study, gullies along major roads were identified from remotely sensed datasets and their volumes and hence the volume of soil loss were estimated in a GIS environment. In addition, biophysical and climatic factors such as vegetation cover, the road contributing surface area, the gradient of the road drainage discharge hillslope and rainfall were identified and derived from remotely sensed datasets using GIS techniques, to find out if they could explain the volume of gullies. The use of remote sensing and GIS technology allowed extraction of information on gully volumes and the possible factors of roadside gully formation (i.e. road contributing areas, hillslope gradient, rainfall and vegetation cover) (Table 7.3). The results indicate that the road contributing area, gradient at the discharge hillslope and vegetation cover for the gully sites were significantly different (ANOVA; $F_{82}=5.830$, $p< 0.05$; $F_{82}= 6.321$, $p< 0.05$; $F_{82}= 29.359$, $p< 0.05$). It was however, observed that the rainfall amount did not vary significantly across different gully sites.

Table 7. 3: Descriptive statistics for gully volumes and the possible factors of road drainage discharge hillslope gully formation

	Minimum	Maximum	Average	Stdev.
Gully volume (m^3)	45.48	1046.89	65.35	16.42
Road contributing area (m^2)	133.19	2800.74	1173.95	639.69
Gradient (°)	4.74	27.39	15.10	5.52
Rainfall (mm)	570	945	738	100
Vegetation cover (%)	15.00	99.00	72.10	25.00

The results further showed that hillslope gradient ($R^2 = 0.69$, $\alpha = 0.00$) and road contributing surface area ($R^2 = 0.63$, $\alpha = 0.00$) have a strong influence on the volume of soil loss along major road in the south-eastern region of South Africa (Figure 7.3). However, factors such as vegetation cover ($R^2 = 0.52$ $\alpha = 0.00$) and rainfall ($R^2 = 0.41$ and $\alpha = 0.58$) have a moderately weaker influence on the overall soil loss (Figure 7.3).

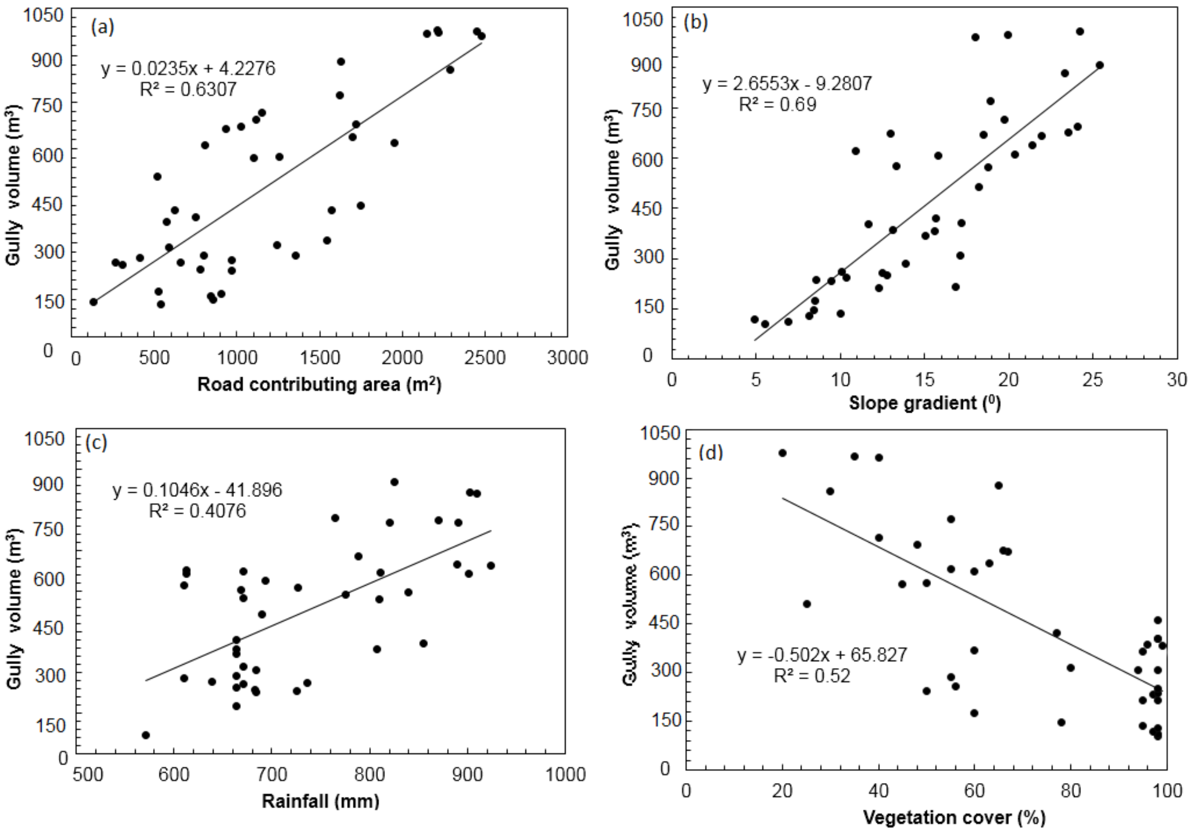

Figure 7. 3: The relationship between gully volumes and (a) road contributing area, (b) gradient, (c) rainfall and (d) vegetation cover of the road drainage discharge areas.

The results of this study demonstrated that road contributing surface area, vegetation cover and hillslope gradient have a significant contribution and influence on the volumes of the gullies along major armoured roads. Moreover, remote sensing and GIS technologies have the capability to investigate the road-related gully erosion where detailed field work remains a challenge due to economic and time constraints. It was therefore concluded that remote sensing datasets can assist in simplifying fieldwork, and to some extent, can even substitute it.

7.5 Assessing the effectiveness of soil erosion control methods on roadcuts

Roadcuts present a potential for negative environmental impacts due to soil loss. For instance, soil loss from roadcuts could cause slope instability (Osorio and De Ona, 2006) and has the potential to pollute water bodies (Sheridan and Noske, 2007). Therefore, soil control on roadcuts is critical to minimise soil loss and the rehabilitation costs. Grace III (2000) has indicated that soil erosion control techniques can reduce sediment yields from roadside slopes by approximately 60%. Hence, several studies have been conducted to evaluate the effectiveness of specific soil erosion control techniques on roadside slopes. However, most studies successfully evaluated the performance of non-engineering soil erosion control methods on roadside slopes (e.g. Grace III, 2002; Benik *et al.*, 2003; Xu *et al.*, 2006; Jankauskas *et al.*, 2012), and evidence of the effectiveness of engineering methods is still limited (e.g. Xu *et al.*, 2009) and so far, no investigation on erosion control on roadcuts has been conducted especially in South Africa.

In this thesis (Chapter 6), the effectiveness of soil erosion control methods utilised on the roadcuts in the south-eastern part of South was evaluated. Twenty slope stabilizing methods and fifteen drainage control techniques were evaluated in terms of performance in controlling soil erosion. A scale of one (1), which means poor performance, to four (4) depicting successful performance was used to evaluate performance of each soil erosion control method. The results of the performance scores showed that the erosion control methods obtained significantly different scores (Figure 7.4).

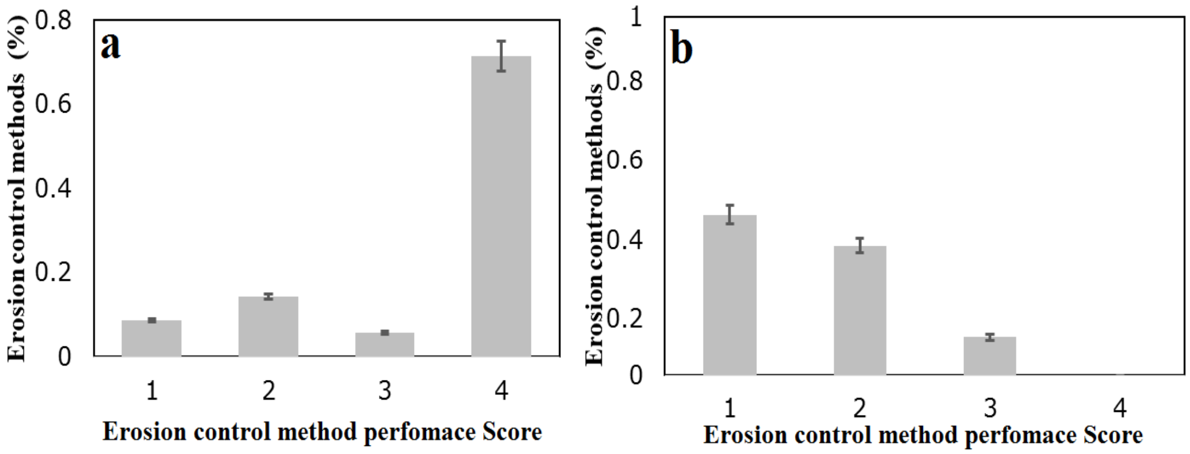

Figure 7. 4: Scores for the performance of (a) roadcut stabilisation methods and (b) drainage canals. Bars represent the percentages, and whiskers represent 95% confidence intervals.

Results show that the highest proportion of slope stabilisation methods (71.5%) obtained a score of four showing an excellent performance, 5.7% obtained a score of three which indicates a good performance, 14.3% obtained a score of two which shows a poor performance, while 8.6% obtained the lowest score of one indicating poor performance. On the other hand, the highest proportion (46.2%) of the evaluated drainage control methods obtained a score of one, indicating a very poor performance, while 38.4% obtained a score of two for poor performance and the remaining 15.4% obtained a score of three for good performance with none of the evaluated methods obtaining a score of four for excellent performance.

The good performance of slope stabilisation methods was enhanced by the ability of these methods to allow vegetation re-establishment on the roadcuts (Figure 7.5a), thereby reducing direct rainfall impact and runoff as well as stabilising the soil by the root system as opposed to drainage canals that did not allow vegetation re-establishment (Figure 7.5b). The results from this study therefore indicate that an ultimate, long term erosion control can be provided through establishment of vegetation cover.

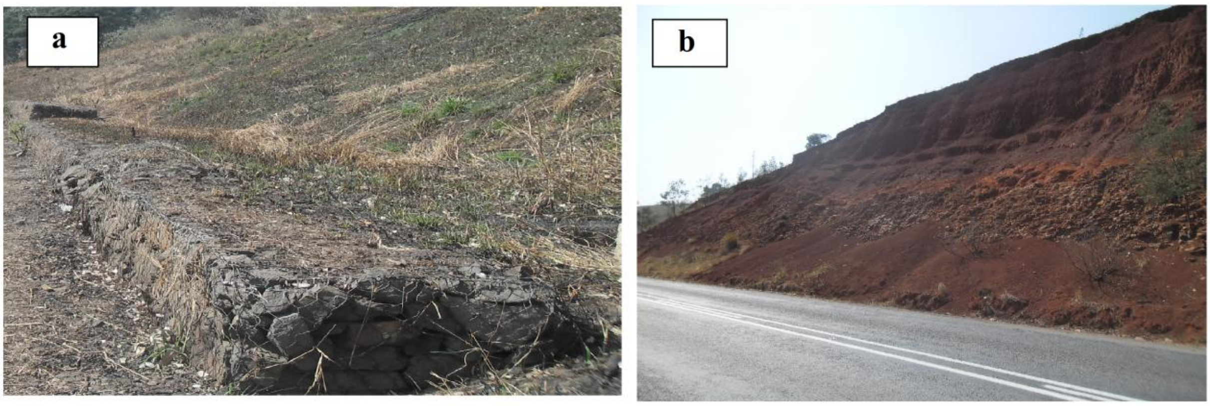

Figure 7. 5: (a) Successful roadcut slope stabilisation erosion control method with fully established vegetation cover and (b) an actively eroding roadcut with minor localised mass movement and sediment deposition at the toe of the roadcut.

7.6 Conclusion

The main focus of this study was to understand soil erosion related to the principal roads in south-eastern South Africa. The main conclusions are based on the finding below, obtained from different objectives addressed in this study.

In this study, the gradient was noted to be significantly higher on degraded roadcuts than on those that were not degraded. Moreover, vegetation cover was significantly lower on degraded roadcuts than on those that were not. This suggests that gradient and vegetation cover of the roadcuts are associated with the presence of rills on the roadcuts. In addition, there was a relationship between the gradient and vegetation cover of the roadcuts, and the rill dimensions. The widths and depths of the rills observed on the roadcuts increased with an increase in slope gradient and a decrease in percentage of vegetation cover.

Relationships have been found between the the volume of soil loss and rill dimensions, with rill depth being the foremost variable in calculating volume of soil loss than rill width and length. This demonstrated that erosion features such as rills can be used to estimate the volume of soil loss. Additionally, soil properties (i.e. exchangeable sodium percentage, sodium adsorption ratio, organic carbon as well as percentage sand and clay contents) were found to explain the volume of soil loss through rill erosion on the roadcuts. Exchangeable sodium percentage, sodium adsorption ratio and percentage sand content positively correlated with the volume of soil loss while there was a negative correlation between the volume of soil loss and organic carbon as well as clay content. Silt content, however, did not show any significant relationship with the volume of soil loss. These results have shown that rill erosion on roadcuts is not only explained by the slope gradient and vegetation cover, but may also be associated with the soil physical and chemical properties.

It has further been shown that the remotely sensed datasets and Geographic Information Systems techniques can be used to investigate the causal relationship between topographic variables, climatic variables, and the volume of road-related gullies in areas where detailed field work remains a challenge due to cost and time constraints. The statistical correlations which have been found between hillslope gradient, road contributing surface area, vegetation cover and the volume of gullies have facilitated an explanation for why gullies of different volumes are observed at road drainage release sites.

Lastly, the results of this study show that the slope stabilisation methods are effective for soil erosion control on roadcuts, although some of the studied methods showed poor performance for erosion control. The effectiveness of slope stabilisation methods was improved by the ability to promote vegetation re-establishment. However, poor performance related to soil erosion control methods is associated with poor application, lack of inspection and maintenance. The results however, have demonstrated that the most effective erosion control method is one that promotes vegetation establishment.

7.7 Recommendations and the need for further research

The study presented in this thesis has enabled an explanation of erosion observed along main roads in the south-eastern South Africa. Road networks, constructed for the provision of effective human mobility and transportation of commodities (Bochet *et al.*, 2010) have resulted in permanent alteration of the geomorphic and hydrological settings of the landscape leading to increased soil erosion (Ramos-Scharron and Macdonald, 2007). While not all attempts to investigate road-related soil erosion focused on the post construction phase of amoured roads, many have shown that soil erosion related to roads occur on roadcuts and road drainage release sites. The findings from this study therefore contribute to existing research and hence further support scientific knowledge of the linkage between infrastructure in general, and soil erosion. In addition, the findings of this study could lay a foundation for possible environmentally sustainable road construction and the formulation of effective soil erosion control measures, as well as guidance for future research.

In order to control road-related erosion as described in this study, it is suggested that as a prerequisite, the hydrological and geomorphological studies of the environmental impacts of roads as well as other infrastructure projects should be carried out at the initial stages. As previously discussed, soil erosion on roadcuts increases with the increase in slope gradient and a decrease in vegetation cover, and the volume of soil loss is determined by the soil properties. It is therefore critical for road construction activities to consider minimizing the gradients as well as re-vegetation of the roadcuts. Moreover, the analysis of soil properties is recommended as it could provide an indication of the vulnerability of soil to erosion as well as give a guidance to the selection of appropriate erosion control methods. Similarly, road construction planners should take into consideration the impacts of concentrated road runoff discharge onto the hillslope.

As it has been previously discussed, concentrated road runoff has the potential to cause gully erosion below the road drain outlet and the magnitude of erosion is influenced mainly by the road contributing area and the gradient of the hillslope where runoff is discharged. Therefore, it is recommended that the frequency of drainage sites along the road surfaces should be increased to minimise the road contributing area to the discharge hillslope. Additionally, road runoff should be dispersed on relatively gentle hillslopes with sufficient vegetation cover. Hence road construction on areas where this is not possible should be avoided. Moreover, where possible, construction of roads that cut across the hillslope profiles should be avoided in order to minimise possible subsurface flow interception by the roadcuts.

Despite soil erosion that has already taken place in the study region, the starting point for reducing erosion should be the application of erosion control methods. This process should be undertaken by both engineers and soil erosion specialists to ensure proper application. It is also suggested that inspection and maintenance should be undertaken at regular basis to ensure proper functioning of these erosion control methods. So far, an effective soil erosion control is the one that facilitates vegetation re-establishment. Overall, an effective road-related soil erosion control can be achieved through formulation and implementation of adequate legislation that comprises the standard specifications for road construction.

The following recommendations are also suggested for future research:

- Thresholds of roadcut gradient, vegetation cover and soil properties for soil erosion on roadcuts should be determined to guide future road construction planners with minimum values to consider before constructing the roads.
- Repeated observations should be made for an accurate description of rill evolution and to determine any significant change in the rill cross-sections.
- The reliability and strength of utilising rill dimensions to estimate the volume of soil loss as compared to other methods such as soil erosion modelling and the use of runoff plots needs to be tested in future studies.
- Additional research is required to measure the actual soil erosion (i.e. sediment yield and runoff) in the presence and absence of erosion control methods in order to obtain quantitative data that would help in determining the amount of soil erosion reduced by erosion control measures and hence the selection of the best erosion control method.
- Runoff and soil properties at different road drainage release sites should be investigated and measured with the aim of relating them to the volume of the gullies. Second is how gully erosion rates change over time at the road drainage release sites. This is because most gully erosion studies have shown that gully erosion rates increase over time and can lead to road to stream linkage that results in sediment delivery to streams. Lastly, an explicit investigation of sediment delivery to stream channels is required to determine the fate of sediment material from the gullies.

By coupling the findings of this study with more detailed investigations of road-related soil erosion, priorities needed for road design, mitigation of the impacts of existing roads and rehabilitation practices can be developed.

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