DEVELOPMENT OF UPDATED DESIGN NORMS FOR SOIL AND WATER CONSERVATION STRUCTURES IN THE SUGAR INDUSTRY OF SOUTH AFRICA

by

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Submitted in partial fulfilment of the academic requirements of

Doctor of Philosophy

in Agricultural Engineering
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Pietermaritzburg
South Africa

February 2020

PREFACE

The research contained in this thesis was completed by the candidate while based in the Discipline of Agricultural Engineering, School of Engineering of the College of Agriculture, Engineering and Science, University of KwaZulu-Natal, Pietermaritzburg, South Africa. The research was financially supported by South African Sugarcane Research Institute.

The contents of this work have not been submitted in any form to another university and, except where the work of others is acknowledged in the text, the results reported are due to investigations by the candidate.

Signed: Professor JC Smithers

Date: 6 May 2020

DECLARATION 1: PLAGIARISM

I, Daniel Otim, declare that:

i. the research reported in this dissertation, except where otherwise indicated or acknowledged, is my original work;

ii. this dissertation has not been submitted in full or in part for any degree or examination to any other university;

iii. this dissertation does not contain other persons' data, pictures, graphs or other information, unless specifically acknowledged as being sourced from other persons;

iv. this dissertation 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, their writing has been placed inside quotation marks, and referenced;

v. where I have used material for which publications followed, I have indicated in detail my role in the work;

vi. this thesis is primarily a collection of material, prepared by myself, published as journal articles or presented as a poster and oral presentations at conferences. In some cases, additional material has been included;

vii. this dissertation does not contain text, graphics or tables copied and pasted from the Internet, unless specifically acknowledged, and the source being detailed in the dissertation and in the References sections.

Signed: D Otim

Date: 6th May 2020

DECLARATION 2: PUBLICATIONS

My role in each paper and presentation is indicated. The * indicates corresponding author.

The following are the list of publications in this thesis:

Chapter 2

Otim, D*, Smithers, JC, Senzanje, A and van Antwerpen, R. 2019b. Design norms for soil and water conservation structures in the sugar industry of South Africa. *Water SA* 45 (1): 29-40.

Chapter 3

Otim, D*, Smithers, JC, Senzanje, A and van Antwerpen, R. 2019a. Assessment of trends in run-off and sediment yield from catchments under sugarcane production and management practices*. *International Sugar Journal* 121 (1443): 216-219.

Chapter 4

Otim, D*, Smithers, J, Senzanje, A and van Antwerpen, R. "In press". Verification of runoff volume, peak discharge and sediment yield simulated using the ACRU model for bare fallow and sugarcane fields. *Water SA* "In press".

Chapter 5

Otim, D*, Smithers, JC, Senzanje, A, van Antwerpen, R and Thornton-Dibb, SLC. "In press". Development and assessment of an updated tool for the design of soil and water conservation structures in the sugar industry of South Africa. *Agricultural Engineering International: CIGR Journal* "In press".

Chapter 6

Otim, D*, Smithers, JC, Senzanje, A and van Antwerpen, R. "In press". Investigation of system design criteria for extreme events leading to most soil loss and the economic impact of varying design return periods. *Applied Engineering in Agriculture* "In press".

Chapter 7

Otim, D*, Smithers, JC, Senzanje, A and van Antwerpen, R. "In press". Impacts of soil and water conservation structures on stream flow reduction in the sugar industry of South Africa. *Water SA* "In press".

The following papers were presented at national and international conferences:

Otim, D*, Smithers, J, Senzanje, A. and van Antwerpen, R. 2019. Verification of runoff volume, peak discharge and sediment yield simulated using the ACRU model for bare fallow and sugarcane fields. In *Proc. of the Proceedings of the Annual Congress-South African Sugar Technologists' Association*, 77-81.

Otim, D*, Smithers, JC, Senzanje, A and van Antwerpen, R. 2018. Assessment of trends in rainfall and runoff at the La Mercy catchments under bare fallow conditions and sugarcane production. In: eds. Akdeniz, RC and Yaldiz, O, *CIGR 2018 XIX. World Congress of CIGR Program and Abstracts' Book*, 201. CIGR, Antalya, Turkey. 22 – 25 April, 2018.

Otim, D*, Smithers, JC, Senzanje, A and van Antwerpen, R. 2018. Verification of runoff volume and peak discharge from sugarcane fields simulated using the *ACRU* model. In: eds. Akdeniz, R and Yaldiz, O, *CIGR 2018 XIX. World Congress of CIGR Program and Abstracts' Book*, 46. CIGR, Antalya, Turkey. 22 – 25 April, 2018.

Otim, D*, Smithers, JC, Senzanje, A and van Antwerpen, R.2018. Assessment of trends in runoff and sediment yield from catchments under sugarcane production and management practices. *Proceedings of South Africa Sugar Technologists'cAssociation*, 98-102. SASTA, Durban, RSA. 14 – 16 August, 2018.

Otim, D*, Smithers, JC, Senzanje, A and van Antwerpen, R.2018. Assessment of trends in runoff, peak discharge and sediment yield from catchments under sugarcane production and management practices. South African Institute of Agricultural Engineers (SAIAE) Symposium and Biennial CPD Event. Durban North, South Africa. 17 – 20, September 2018.

In all the above papers and manuscripts, I reviewed, summarised and synthesised the literature and wrote the papers and manuscripts. My co-authors, Prof JC Smithers, Dr A Senzanje and Prof R van Antwerpen provided guidance and reviewed the papers and manuscripts.

Mr SLC Thornton-Dibb contributed to the manuscript in Chapter 5 by setting up and automating the Agricultural Catchments Research Unit (*ACRU*) model, thus enabling timely and speedy simulations.

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Signed: D Otim

Date: 6th May 2020

ABSTRACT

Sugarcane in South Africa is grown on wide-ranging soils, sometimes in non-ideal climates and on steep topographies where soils are vulnerable to erosion. A consequence of unsustainable soil loss is reduction in field production capacity. Sugarcane fields are protected against erosion through, *inter alia*, the use of engineered contour banks, waterways and spill-over roads. A comparison of design norms in the National Soil Conservation Manual and norms used in the sugar industry clearly shows discrepancies (*e.g*. maximum slope and cover factor of sugarcane) that need to be investigated. Furthermore, the sugar industry design nomograph was developed based on an unsustainable soil loss limit, does not include any regional variations of climate and the impact on soil erosion and runoff and does not include vulnerability during break cropping. The aim of this research was to develop updated design norms for soil and water conservation structures in the sugar industry of South Africa. Many soil loss models exist, of which empirical models are the most robust and provide stable performances. The Modified Universal Soil Loss Equation (MUSLE) which is embedded in the Agricultural Catchments Research Unit (*ACRU*) model, estimates event-based soil erosion and, given that the majority of soil erosion occurs during a few extreme events annually, the design norms were updated using the MUSLE. The *ACRU* model is a daily time step, physical-conceptual agrohydrological model. Runoff volume, peak discharge and sediment yield were simulated with the *ACRU* model and verified against the respective observed data. The results showed good correlations and the *ACRU* model can be confidently applied in the development of updated design norms for soil and water conservation structures in the sugar industry of South Africa. The *ACRU* model was used to conduct simulations for the different practices in the sugar industry and the results used to build the updated tool for the design of soil and water conservation structures in the sugar industry of South Africa, using MS Access with a background database and a graphical user interface. The updated tool is robust, based on sustainable soil loss limits, includes regional variations of climate and their impact on soil erosion and runoff and also includes vulnerability during break cropping. It is more representative of conditions in the sugar industry of South Africa and therefore recommended for use in place of the current sugar industry design norms. The results also indicate that soil and water conservation structures result in insignificant reductions in stream flow and would not likely necessitate their declaration as Stream Flow Reduction (SFR) activities as contained in the National Water Act of South Africa. Consequently, a 20 year return period is recommended for the design of soil and water conservation structures and the cost implication of varying design return periods from the minimum 10 year return period to the 20 year return period ranges from 16% to 35% across the four homogenous regions in the sugar industry of South Africa.

ACKNOWLEDGMENTS

I am highly indebted to South African Sugarcane Research Institute (SASRI) for funding this research. Without this funding it would not have been possible for me to pursue studies at the University of KwaZulu-Natal (UKZN).

I also wish to express my gratitude to the following persons and institutions for the support granted during this study:

a) Prof JC Smithers, my supervisor, for the guidance, continuous support and positive energy during this study. Thank you.
b) Dr A Senzanje and Prof R van Antwerpen, my co-supervisors for their endless support, input and advice.
c) Prof RE Schulze for his expert opinions and guidance at the various stages.
d) Mr N Davis for extracting and collating climatic data from the relevant data bases.
e) Mr SLC Thornton-Dibb for his assistance in setting up and automating the Agricultural Catchments Research Unit (*ACRU*) model, thus enabling timely and speedy simulations.
f) Mrs K Smithers for her assistance in reviewing and refining the algorithms embedded in the Contour Spacing Design Tool (CoSDT).
g) Dr P Tweddle from SASRI for guidance in costing soil and water conservation structures.
h) Ms I Thompson and Ms A Makhaye from SASRI and Mr D Wilkinson and Ms N Gumede from Noodsberg Cane Growers Association for provision of Land Use Plans for various areas in the sugar industry.
i) UKZN for availing office space, internet access and stationary.
j) My family and colleagues for the support and encouragement extended to me throughout this study.
k) My parents, Dan and Kate Opito, for the support they have continued to give me in my pursuit of quality education.
l) My wife, Josephine, and our two children for their love, patience and support, including the numerous sacrifices made while I accomplished my studies. I love you.

Above all, acknowledgement goes to God, my Heavenly Father for giving me the opportunity, knowledge, strength and wisdom to pursue my studies. All glory and honour is yours. Amen.

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LIST OF ACRONYMS

ACRU	Agricultural Catchments Research Unit
ARC	Agricultural Research Council
CARA	Conservation of Agricultural Resources Act
CoSDT	Contour Spacing Design Tool
DAERD	Department of Agriculture, Environmental Affairs and Rural Development
DARD	Department of Agriculture and Rural Development
DAWS	Department of Agriculture and Water Supply
KZN	KwaZulu – Natal
LUP	Land Use Plan
MAP	Mean Annual Precipitation
MAR	Mean Annual Runoff
MUSLE	Modified Universal Soil Erosion Equation
NRCS	Natural Resources Conservation Service
NVFFA	National Veld and Forest Fire Act
NWA	National Water Act
RUSLE	Revised Universal Soil Erosion Equation
SA	South Africa
SASA	South African Sugar Association
SASEX	South African Sugar Association Experiment Station
SASRI	South African Sugarcane Research Institute
SCDSS	Sugarcane Decision Support System
SCS	Soil Conservation Service
SCS-SA	Soil Conservation Service – South Africa
SFR	Stream Flow Reduction
SFRA	Stream Flow Reduction Activities
SLEMSA	Soil Loss Estimator for Southern Africa
UKZN	University of KwaZulu – Natal
USDA	United States Department of Agriculture
USLE	Universal Soil Erosion Equation

1 INTRODUCTION

This chapter contains background to the study on the development of updated design norms for soil and water conservation structures in the sugar industry in South Africa. It covers the rationale, objectives of the study that include the research aim and specific objectives and an outline of the thesis structure.

1.1 Background

Soil erosion is a serious problem emanating from a combination of agricultural intensification, soil degradation and intense rainstorms (Amore *et al.*, 2004). Moreover, when the rate of soil loss is unsustainable, it leads to a reduction in crop yield and hence the need to limit soil losses to sustainable levels (Russell, 1998b). The mechanical means of soil conservation in the South Africa sugar industry is by use of contour banks and waterways (Platford, 1987), and the standards and guidelines for the design of soil conservation structures were published by SASA (2002). The nomograph for the design of soil and water conservation structures in the sugar industry of South Africa was developed by Platford (1987) who used observations from runoff plots and the long term average annual soil loss simulated using the Universal Soil Loss Equation (USLE) (Wischmeier and Smith, 1965; Wischmeier and Smith, 1978). The USLE aggregates soil loss and yet erosion occurs on an event basis (Schulze, 2013). The Modified Universal Soil Loss Equation (MUSLE) (Williams, 1975b) on the other hand is an event based model (Williams and Arnold, 1997).

The sugar industry design norms for spacing of contour banks advocate that specific designs should be used to design soil conservation structures for slopes less than 3% or greater than 30% (Russell, 1994), although the sugar industry design nomograph includes slopes of up to 40% (Platford, 1987; SASA, 2002). There are also differences between the design norms contained in the National Soil Conservation Manual (van Staden and Smithen, 1989; DAWS, 1990) and design norms used in the sugar industry (Platford, 1987; SASA, 2002) (*e.g.* maximum slope and cover factors for sugarcane). In addition, a 10 year return period is specified by SASA (2002) for the design of soil and water conservation structures. The sugar industry design nomograph does not (Smithers, 2014):

(a) include any regional variations of climate and the impact on soil erosion and runoff,

(b) account for large runoff events and how frequently these occur, and

(c) include vulnerability during break cropping where the cover may be reduced.

In addition to the above, Platford (1987) used an acceptable soil loss of 20 $t.ha^{-1}.year^{-1}$ in the development of the nomograph, which is not sustainable considering that sustainable soil losses range between 5 and 10 $t.ha^{-1}.year^{-1}$ based on 250 mm soil depth for sustainable crop production (Matthee and Van Schalkwyk, 1984; Le Roux *et al.*, 2008). It is not clear as to why an unsustainable soil loss was used by Platford (1987), but it is suspected that it was considered more economic to implement wider spaced structures which result from design rules with the higher acceptable loss. For the above reasons, there is a need to update the design methodologies or norms currently used in the sugar industry.

1.2 Rationale

Unsustainable soil loss from a field results in a reduction in crop yield. Thus the need to limit soil losses to levels that are sustainable through the use of soil and water conservation structures and management practices. SASA (2002) published standards and guidelines for the design of soil and water conservation structures in the sugar industry of South Africa and they include a nomograph developed by Platford (1987) for the design of soil and water conservation structures. The design norms employed by the sugar industry specify a 10 year return period although the adequacy of the 10 year return period specified is questionable owing to the projected increase in the frequency of occurrence of extreme events in South Africa. The design norms also advocate for specific designs whenever slopes are less than 3% or greater than 30%, although the design nomograph caters for slopes up to 40%. Discrepancies between design norms in the National Soil Conservation Manual (van Staden and Smithen, 1989; DAWS, 1990) and norms used in the sugar industry exist and there is a need to accommodate regional change variations in climate, account for significant events of soil erosion, production and management practices, and regional differences in soils and slopes. Furthermore, there is a need to maintain soil losses within sustainable limits. Thus, the purpose of this research aims to develop updated design norms for soil and water conservation structures in the sugar industry of South Africa.

1.3 Aim

The aim of this research is to develop updated design norms for soil and water conservation structures in the sugar industry of South Africa.

1.4 Specific Objectives

In order to achieve the aim of this research, the following specific objectives have to be met:

(a) to review current internationally accepted models for simulating soil losses, the application of the selected model to determine design approaches, and norms for the industry,

(b) to establish regional differences in climate, topography and soils in South Africa to be included in the design norms,

(c) to determine design approaches and norms for topographies found in the local sugar industry,

(d) to develop the design norms that include sugar production systems which include crop rotations,

(e) to determine design criteria for extreme events when most soil loss occurs and the economic impact of varying design return periods, and

(f) to investigate the impacts of soil and water conservation structures on water related legislation, including stream flow reduction activities.

1.5 Originality of the Study

Innovations from this research includes a new and updated tool, herein termed the Contour Spacing Design Tool (CoSDT) for the design of soil and water conservation structures in the sugar industry of South Africa. The CoSDT is robust but simple to apply, is based on sustainable soil loss limits, includes regional variations of climate and their impact on soil erosion and runoff and also includes vulnerability during break cropping.

1.6 Outline of thesis structure

Each chapter is presented in the format of a draft of published journal paper, containing an abstract, a short literature review, data and methods, results and discussion and conclusions. Aspects of soil and water conservation are central to all chapters. An overview of the various chapters is presented below.

Chapter 2 is based on a paper published in January 2019 in the *Water SA* Journal and it presents a critical review of the design norms for soil and water conservation structures in the sugar industry of South Africa.

Cognisant of the fact that the development of updated design norms for soil and water conservation structures in the sugar industry of South Africa would require simulations of runoff, peak discharge and sediment yield, Chapter 3 seeks to establish a clean data set for verifications conducted in Chapter 4, and to increase understanding of hydrological and soil erosion processes from bare fallow and catchments under various sugarcane production management practices. Part of the content of Chapter 3 is based on a paper published in the *International Sugar Journal* in March 2019.

In acknowledging the findings and recommendations from Chapters 2 and 3, Chapter 4 contains results from the verification of event runoff volume, peak discharge and sediment yield simulated by the Agricultural Catchments Research Unit (*ACRU*) model against observed data from catchments in South Africa under both bare fallow and sugarcane land cover conditions and with various management practices. The findings show that the *ACRU* model can be confidently applied in the development of updated design norms for soil and water conservation structures in the sugar industry in South Africa.

Based on the findings in Chapter 4, Chapter 5 covers the development and assessment of an updated tool for the design of soil and water conservation structures in the sugar industry of South Africa. A comparison of the design of soil and water conservation structures prepared by experts in the sugar industry and with the design tool are also presented in Chapter 5.

In Chapter 6, an investigation of system design criteria for extreme events when most soil loss occurs, and the economic impact of varying design return periods, is presented.

Chapter 7 presents investigations of the impacts of soil and water conservation structures on stream flow reduction activities in the sugar industry of South Africa.

A synthesis of all information discussed in Chapters 1 to 7, as well as discussions, conclusions and recommendations for further research is presented in Chapter 8.

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2 DESIGN NORMS FOR SOIL AND WATER CONSERVATION STRUCTURES IN THE SUGAR INDUSTRY OF SOUTH AFRICA

This Chapter was published as:

Otim, D, Smithers, JC, Senzanje, A and van Antwerpen, R. 2019b. Design norms for soil and water conservation structures in the sugar industry of South Africa. *Water SA* 45 (1): 29-40.

Abstract

This paper contains a critical review of the norms employed in the design of soil and water conservation structures in the South African sugar industry and highlights research needs in order to update them. Sugarcane in South Africa is grown on wide-ranging soils, sometimes in non-ideal climates and on steep topographies where soils are vulnerable to erosion. A consequence of unsustainable soil loss is reduction in field production capacity. Sugarcane fields are protected against erosion through, *inter alia*, the use of engineered waterways, contour banks and spill-over roads. The South African Sugarcane Research Institute (SASRI), previously known as the South African Sugar Experiment Station (SASEX), developed a nomograph to easily compute the maximum width of field panels based on soil type, tillage method, replant method, surface structures to control runoff, surface cover and slope. This was followed by guidelines and norms for the design of soil and water conservation structures. However, the nomograph was developed based on an acceptable soil loss of 20 $t.ha^{-1}.year^{-1}$ and yet sustainable soil loss rates based on 250 mm of top soil range between 5 and 10 $t.ha^{-1}.year^{-1}$. Comparisons between design norms in the National Soil Conservation Manual and norms used in the sugar industry clearly show discrepancies that need to be investigated. The design of soil conservation structures includes the design of both contour bank spacing and hydraulic capacity. The sustainable soil loss method is recommended in the design of contour spacing and it determines contour spacing based on evaluation of site specific sheet and rill erosion potential of the planned contour spacing, while the hydraulic design employs Manning's equation. Considering that increases in both design rainfall and design floods are anticipated in South Africa, it is necessary to incorporate these projections in the design of soil and water conservation structures. Many soil loss models exist, of which empirical models are the most

robust and provide stable performances. The majority of empirical models are lumped models which estimate average annual soil loss. The Modified Universal Soil Loss Equation (MUSLE) estimates event based sediment yield and, given that the majority of soil erosion occurs during a few extreme events annually, the design norms should be updated using the MUSLE.

Keywords: contour banks, hydraulic, hydrologic, soil erosion, USLE, waterways

2.1 Introduction

Soil conservation is defined as the prevention and reduction of the amount of soil lost through erosion (Sustainet, 2010). The purpose of soil conservation is to ensure that the rate of soil formation is not exceeded by the rate of soil loss (Morgan, 2005), and it ensures increases in the amount of water seeping into the soil, thereby slowing down and reducing the amount of water running off (Sustainet, 2010). Soil is the most important resource on which agriculture is based. Thus, the proper management of soil is vital to ensure long term sustainability of agricultural productivity. According to Morgan (2005), soil erosion control is dependent on the selection of appropriate strategies for soil conservation which in turn requires a thorough understanding of the processes and mechanics of erosion. Many soil conservation practices exist and they include mechanical structures (*e.g.* contour bunds, terraces, check dams), soil management practices and agronomic measures (*e.g.* cover crops, tillage, mulching, vegetation strips, re- vegetation, and agroforestry) (Krois and Schulte, 2014). It is recommended that all approaches of soil conservation *i.e.* agronomic, soil management and mechanical means be used to manage runoff from cultivated lands (Reinders *et al.*, 2016). Erosion is the process by which soil particles are detached and transported by erosive agents (Ellison, 1944). When the erosive agent is rainfall and/ or runoff, the process is referred to as soil erosion by water (Ferro, 2010). Erosion of soil is a serious problem that emanates from a combination of agricultural intensification, soil degradation and intense rainstorms (Amore *et al.*, 2004). Soil is functionally a non- renewable resource and while topsoil develops over centuries, the world's growing human population has actively depleted the resource over decades (Cohen *et al.*, 2006). According to Cogo *et al.* (1984), soil erosion from cultivated cropland continues to be a major concern with significant associated problems, which range from the losses of a non- renewable resource and nutrients at its source to the contamination that occurs in downstream areas (Guo *et al.*, 2015). Shabani *et al.* (2014) reported that soil erosion is one of the most important factors degrading fertile agricultural soils around the world. According to Lewis (1981) and Nyakatawa *et al.* (2001), erosion may lead to the development of a rough and thin soil layer having little or no capacity to store water. This reduces soil fertility thereby resulting in land degradation and environmental problems (Sutherst and Bourne, 2009). The average predicted soil erosion rate in South Africa based on the general pattern of relative differences is 12.3 $t.ha^{-1}.year^{-1}$ (Le Roux *et al.*, 2008), while the rate of soil formation within favourable conditions based on a 40 year period is in the range 0.25 to 0.38 $t.ha^{-1}.year^{-1}$ for each millimetre of top soil (Matthee and Van Schalkwyk, 1984). Similarly, Australia has an average soil erosion rate of 4.1 $t.ha^{-1}.year^{-1}$ (Le Roux *et al.*, 2008) and soil formation rates below 0.5 $t.ha^{-1}.year^{-1}$ in the eastern regions and effectively zero in the other areas (Edwards, 1988). The USA has an average soil erosion rate of 15.1 $t.ha^{-1}.year^{-1}$ and soil formation rates over 5 $t.ha^{-1}.year^{-1}$ (Magleby *et al.*, 1995). However, the concept of an average erosion rate on a continental scale is illogical because of temporal and spatial variability in erosion rates (Boardman, 1998). Unsustainable soil loss from a field results in a reduction in the capacity of the field to sustain crop yield (Russell, 1998b).

Research on soil erosion only started in 1915 in the USA which has continued to lead the world in this field (Matthee and Van Schalkwyk, 1984). According to Haylett (1961), research to determine the effects of soil cover on runoff and erosion was started in 1929 in South Africa. Many studies have since then tried to estimate the historical and current soil and subsequent soil water holding capacity losses in the country due to soil erosion (Matthee and Van Schalkwyk, 1984). For example, Platford (1979) conducted research focusing on soil and water losses from sugarcane fields in South Africa to produce recommendations for protective practices. Various studies in the area of soil and water losses in South Africa are also documented in literature (*e.g.* Schulze and Arnold, 1979; McPhee *et al.*, 1983; Platford and Thomas, 1985; Platford, 1987; Haywood and Schulze, 1990; Haywood, 1991; Russell, 1994; Russell and Gibbs, 1996; Smithers *et al.*, 1996).

According to Platford (1987), sugarcane in South Africa is regularly grown in diverse climatic and topographic conditions and on a range of soils. Soils in sugarcane growing areas are predominantly granular, leached and are characterised by high rates of erosion after the removal of the natural vegetation. Protection of cropped land in areas experiencing high rainfall has traditionally been provided by water carrying terrace banks built across the hillside at gentle slopes, but sugarcane is not always grown on relatively gentle slopes for which this control system was designed (Platford, 1987). Therefore, strip planting, rotational crops, reduced tillage and other management practices which provide sufficient protection should be used in place of, or in addition to, terrace banks.

SASA (2002) developed guidelines and norms for the design of land use plans in the sugar industry, which includes soil conservation structures (*e.g.* waterways, contour banks and spill-over roads), surface water management and cane extraction road networks. The nomograph included for the design of soil and water conservation structures as shown in Figure 2.1, was developed by Platford (1987), who used observations from runoff plots, small catchments and the long term average annual soil loss estimated using the Universal Soil Loss Equation (USLE) (Wischmeier and Smith, 1965; Wischmeier and Smith, 1978). The USLE is a model widely used in the estimation of soil erosion and supporting soil conservation measures (Song *et al.*, 2005) and it is the standard technique for soil conservation workers (Morgan, 2005).

The sugar industry design norms for spacing of contour banks advocate that specific designs should be used to design soil conservation structures for slopes less than 3% in irrigated areas by adopting parallel conservation terraces or greater than 30% (Russell, 1994; SASRI, 2015), although the sugar industry design nomograph includes slopes of up to 40% (Platford, 1987; SASA, 2002). There are also differences between the design norms contained in the National Soil Conservation Manual (van Staden and Smithen, 1989; DAWS, 1990) and design norms used in the sugar industry (Platford, 1987; SASA, 2002) (*e.g.* maximum slope and cover factors for sugarcane). The sugar industry design nomograph does not (Smithers, 2014):

(a) include any regional variations of climate and the impact on soil erosion and runoff,
(b) account for large runoff events and how frequently these occur,
(c) account for unplanned events (*e.g.* runaway fires) which do occur,
(d) include vulnerability during break cropping where the cover may be reduced, and
(e) include the potential impact of climate change on runoff and soil loss.

In addition to the above, Platford (1987) used an acceptable soil loss of 20 $t.ha^{-1}.year^{-1}$ in the development of the nomograph, which is not sustainable. It is not clear as to why an un sustainable soil loss was used by Platford (1987), but it is suspected that it was considered more economic to implement wider spaced structures which result from design rules with the higher acceptable loss. For the above reasons, there is a need to update the design methodologies/ norms currently used in the sugar industry.

The main aim of this article is to review the design norms for soil and water conservation structures in the South African sugar industry, compare and contrast the norms with national norms and international practices and to identify research gaps required to update the current design norms.

2.2 Agronomic Practices in the Sugarcane Production System

Sugarcane production systems in South Africa involve activities ranging from land preparation to the transportation of the harvested crop to the mill (SASRI, 2011). A typical production cycle lasts for about ten years which is the time frame that allows a farmer to maintain the economic viability of sugarcane (Platford, 1987; SASA, 2002; SASRI, 2015). The agronomic practices which constitute production systems in the sugar industry include land preparation, planting, weed, pest and disease control, and harvesting of sugarcane (SASA, 2002). Sugarcane production systems are briefly discussed to illustrate the relevance and/ or the impact of management practices on design considerations for soil conservation.

2.2.1 Land preparation

According to Meyer (2005), the goal of land preparation is to produce a tilth which results in good bud germination and subsequent root development of the new crop. Land preparation includes conventional tillage and minimum tillage practices. SASRI (1998) and SASA (2002), advocate for minimum tillage practices on slopes greater than 11% for erodible soils, slopes greater than 13% for moderately erodible soils and slopes greater than 16% for resistant soils. On the other hand, conventional tillage is acceptable on slopes with smaller gradients as long as ploughing is conducted across the slope and not up and down the slope (SASA, 2002).

2.2.2 Planting

Planting of sugarcane can be done either by hand (manually) or mechanically (Meyer, 2005). SASEX (1974) advocated for sugarcane strip planting and harvesting across all steep slopes other than short run slopes which are in, and adjacent to, valley bottoms. Strip planting involves growing various plant species in adjacent panels (Głowacka, 2014). Planting of sugarcane in strips is practiced so as to minimise soil loss and it is recommended on all slopes exceeding 2% except on certain layouts used for irrigation (SASRI, 2015). However, where strip planting is not practiced, dimensions and location of conservation structures have been adjusted in conformity with the SASA (2002) nomograph. According to SASA (2002) and SASRI (2015), the strip widths at right angles to the contour should not exceed thrice the maximum distance between contour banks as long as the alternate strips have a difference in age which is not less than six months. SASA (2002) and SASRI (2015) further stress the need for alternate strip planting to be practiced on all slopes greater than 12%.

2.2.3 Weed, Pest and Disease Control

Weed control is achieved either by mechanical means or via spraying of chemicals while pest and disease control is achieved through manual and mechanical application of chemicals. Both conventional tillage and conservation tillage practices are vital in the control of weeds but it is conservation tillage which ensures soil and water conservation through maintaining as much crop residue as possible on the soil surface (Russell, 1998a). The crop residues reduce the impact of raindrop splash on the soil surface, reduce the velocity of surface runoff and protect the soils from erosion. Crop rotation is a practice which is required for the control of pests and diseases (Sustainet, 2010). According to SASRI (2015), land should be used in accordance with a crop rotation system so as to promote addition of organic matter to soils, soil fertility, reduction of pests and diseases, and erosion control. Crop rotation is achieved through growing secondary crops that enhance soil health. Generally after five to six harvests, sugarcane yield might have been decreased significantly thus calling for rejuvenation of the field (Zuurbier and Van de Vooren, 2008). Rejuvenation of a sugarcane field is usually performed by planting an annual leguminous food crop. The legumes improve soil quality, prevent soil erosion and contribute to food production (Zuurbier and Van de Vooren, 2008).

2.2.4 Harvesting

Harvesting of sugarcane should be planned so as to minimise negative environmental impacts and equipment having the least impact on the environment should be used (SASA, 2002). Burning and mulching are alternative sugarcane harvesting procedures practiced in South Africa (SASRI, 2015). The burning of sugarcane prior to harvesting is a widespread practice in South Africa and the main reason is to eliminate excess residue so as to improve harvesting, handling and milling of the cane (SASRI, 2010). Approximately 90% of sugarcane in South Africa is burnt at harvest with the rest harvested green (SASRI, 2013). According to SASRI (2014), accidental and runaway fires are common occurrences and often spread over entire hillsides, thereby exposing the land to potential erosion. Serious erosion can be experienced if heavy rains follow soon after burning, thus making it necessary to leave the tops and residues scattered over the soil surface so as to protect the soil and reduce the velocity of runoff (SASRI, 2014). It is a requirement for all burning to comply with the Conservation of Agricultural Resources Act (CARA, 1983) and the National Veld and Forest Fire Act (NVFFA, 1998). In addition, codes of practice on burning which provide acceptable ways of complying with legislation and minimising negative impacts on the environment while aiding crop production are in place (SASRI, 2013). Burning of sugarcane at harvest is associated with a number of disadvantages compared to green cane harvesting and it should be avoided wherever possible (SASRI, 2010; SASRI, 2013). Soil and water conservation and yield improvement are some of the benefits associated with green cane harvesting, among others (SASRI, 2010). SASA (2002) and SASRI (2015) advocate for mulching wherever possible for maximum conservation of soil and water, particularly on steep slopes and erodible soils.

In summary, the agronomic practices in the sugarcane production systems discussed above play a role in soil and water conservation and they should be considered when updating design norms for soil and water conservation structures in the sugar industry.

2.3 Design for Soil and Water Conservation Structures

Design norms are guidelines applied in the design of structures. The commonly used structures in soil and water conservation are waterways and contour banks and their designs entail both hydrologic and hydraulic designs.

2.3.1 Hydrologic design

Hydrologic design entails estimation of design floods which is important in the sizing of hydraulic structures and thus to quantify and limit the risk of failure of the structures (Reinders *et al.*, 2016). The risk of failure is related to the return period and it is quantified as a probability of exceedance, as shown in Equation 2.1.

$$P_e = \frac{1}{T} \qquad (2.1)$$

where

P_e = risk of failure

T = return period (years)

ASABE (2012) recommended a 10 year return period, 24 hour storm for the design of contour banks but stresses the need for the selection of larger design storms appropriate to the level of risk of failure. A 10 year return period is also recommended for the design of soil conservation structures in Australia and in situations where failure would threaten public safety or lead to severe damage, larger return periods are recommended (Carey *et al.*, 2015).

Matthee and Van Schalkwyk (1984) recommended that soil conservation structures should be designed so as to cope with 10 – 25 year return period floods while SASA (2002) specifies a 10 year return period for the design of soil and water conservation structures in the South African sugar industry.

According to Russell (1994), the Soil Conservation Service (SCS) method (SCS, 1972) of runoff estimation should be used for the design of structures on cultivated land while the Rational Method (Kuichling, 1889) is to be used for storage dam and gulley stabilization design in natural catchments. The SCS method (Equation 2.2) is widely used and it is not as sensitive to user inputs as the Rational Method (Equation 4) (Smithers, 2012). Schmidt *et al.* (1987) utilised the developments and verifications by Schulze and Arnold (1979), Schulze (1982), Schmidt and Schulze (1984) and Dunsmore *et al.* (1986) to adapt the SCS method for application in South Africa (SCS-SA) which included additional soil classes, temporal distribution of rainfall and the impact of antecedent moisture conditions on runoff generation in South Africa.

$$Q = \frac{(P - I_a)^2}{P - I_a + S} \text{ for } P > I_a \qquad (2.2)$$

where

Q = stormflow depth (mm),

P = daily rainfall depth (mm),

I_a= initial abstraction prior to stormflow commencement (0.1S for South Africa) (mm), and

S = potential maximum soil water retention (mm).

The peak discharge estimated using the SCS-SA approach depends on storm flow depth, catchment area, catchment lag time, and the effective storm duration shown in Equation 2.3 (Schulze and Schmidt, 1995).

$$q_p = \frac{0.2083AQ}{\frac{D_e}{2} + L} \tag{2.3}$$

where

q_p = peak discharge ($m^3.s^{-1}$),

A = catchment area (km^2),

Q = stormflow depth (mm),

D_e = effective storm duration (h), and

L = catchment lag time (h).

The Rational Method is extensively used worldwide for both small rural and urban catchments (Alexander, 2001). Parak and Pegram (2006) reported that the Rational method is the most widely used method for estimating design peak discharges from rainfall events and it is easy to understand and simple to use. The method which only computes flood peaks, is sensitive to the input design rainfall intensity and the runoff coefficient, whose selection is based on the experience of the user (Smithers, 2012). The algorithm for the Rational Method is shown in Equation 2.4.

$$q_p = \frac{CIA}{3.6} \tag{2.4}$$

where

q_p = peak discharge ($m^3.s^{-1}$),

C = runoff coefficient,

I = rainfall intensity over catchment ($mm.h^{-1}$), and

A = area of catchment (km^2).

2.3.2 Hydraulic Design

The hydraulic design of soil and water conservation structures entails selecting the placement, size, shape and slope of physical protection works, namely contour banks and waterways.

2.3.2.1 Contour bank design

According to SASEX (2002), contour banks are defined as structures designed hydraulically and placed in the field to protect the land situated immediately below. Design of contour banks involves the selection of vertical and horizontal spacing between contour banks, and the sizing of the contour to safely convey the design discharge (Reinders *et al.*, 2016).

2.3.2.1.1 Spacing of contour banks/ conservation terraces

Two methods namely, vertical interval method and sustainable soil loss method are employed in the determination of contour bank spacing (ASABE, 2012).

The vertical interval method is an empirical method developed by the SCS in the 1950s and it is not soil, cropping system, or rainfall specific (ASABE, 2012). The existing land slope is the slope used in the equation and thus the method does not account for the effect of terrace shape on the constructed land slope. Frequently the maximum conservation terrace spacing computed by use of the vertical interval method is more conservative than that obtained using the sustainable soil loss method (ASABE, 2012). The vertical interval equation is shown in Equation 2.5.

$$VI = XS + Y \qquad (2.5)$$

where

VI = vertical interval (m),

X = variable ranging from 0.4 to 0.8 for graded terraces and 0.8 for terraces that are level (ASABE, 2012),

= variable with limits ranging from 0.10 to 0.60 for South Africa (Matthee and Van Schalkwyk, 1984),

Y = variable ranging from 0.304 to 1.22 depending on erodibility of soil, cropping systems and practices of crop management (ASABE, 2012),

= variable within limits ranging from 0.30 to 2.30 recommended for South Africa depending on soil erodibility, crop nature and cropping system (Matthee and Van Schalkwyk, 1984), and

S = land slope (%).

With the *VI* known, the Horizontal Interval (*HI* in m) is obtained using Equation 2.6.

$$HI = \frac{100VI}{S} \qquad (2.6)$$

where

HI = horizontal interval (m), and

VI = vertical interval (m).

Equation 2.5 was developed in USA with factors *X* and *Y* based on runoff and soil loss experiments (Reinders *et al.*, 2016). van Staden and Smithen (1989) recommended Equation 2.7 for use in South Africa.

$$VI = 0.1S + 0.61 \qquad (2.7)$$

where

VI = vertical interval (m), and

S = land slope (%).

The sustainable soil loss method is the preferred method for determining contour bank spacing and it determines contour spacing based on evaluation of site specific sheet (inter-rill) and rill erosion potential of the planned contour spacing by employing a sheet and rill erosion prediction tool such as the Revised Universal Soil Loss Equation - Version 2 (RUSLE2) (ASABE, 2012). The RUSLE2 (USDA-ARS, 2001) is the model used by the Natural Resources Conservation Service (NRCS) in the computation of site specific sheet and rill erosion based on local climate, soil types, planned cropping system, and slope (USDA-NRCS, 2011). The maximum allowable spacing for contour systems is based on the NRCS planning criteria for the maximum allowed sheet and rill erosion rate for the site and the value is termed tolerable soil loss (USDA-NRCS, 2011). Various tolerable soil loss values within South Africa are documented in literature as shown in Table 2.1.

Table 2.1 Soil loss tolerances in South Africa

Source	Soil loss ($t.ha^{-1}.year^{-1}$)
Hudson (1981)	2[a] – 11
Matthee and Van Schalkwyk (1984)	(5 – 10)[b]
Platford (1987)	4[c] – 12[d]
van Staden and Smithen (1989)	3[e] – 9[f]
Le Roux *et al.* (2008)	10[g]

[a] Recommended for particularly sensitive areas where soils are thin or highly erodible

[b] Based on 250 mm soil depth for sustainable crop production

[c] Recommended for shallow profile soils in the sugar industry

[d] Recommended for deep profile soils in the sugar industry

[e] Recommended for sandy shallow soils underlying topsoil

[f] Recommended for heavy deep soils underlying topsoil

[g] Based on deep alluvial soils

Platford (1987) employed the USLE together with an acceptable soil loss of 20 $t.ha^{-1}.year^{-1}$ in the development of a nomograph to determine contour bank spacing in the South African sugar industry. The algorithm for the USLE is shown in Equation 2.8 and the nomograph for determining contour bank spacing in the South African sugar industry is shown in Figure 2.1.

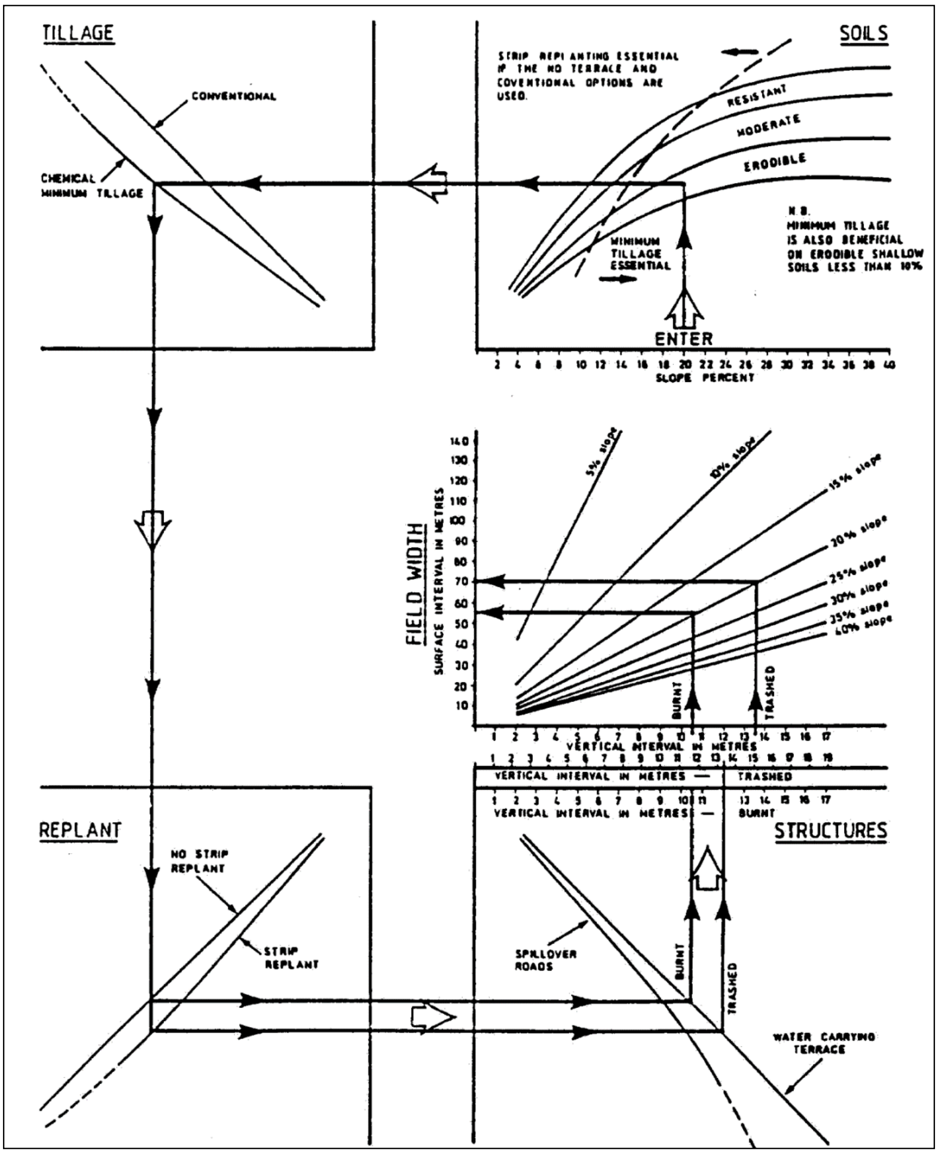

Figure 2.1 Nomograph for determining contour bank spacing in sugarcane fields (Platford, 1987)

$$A_y = RKLSCP \tag{2.8}$$

where

A_y = average annual soil loss (t.ha^{-1}.year^{-1}),

R = annual rainfall-runoff erosivity factor (MJ.ha^{-1}.mm.h^{-1}),

K = soil erodibility factor (t.MJ^{-1}.h.mm^{-1}),

L = slope length factor,

S = slope gradient factor,

C = crop factor, and

P = conservation practice factor.

If A_y is the acceptable soil loss for a specific field, then R, K and S can be fixed and the USLE equation solved for either L with a known C or C solved with a defined L (Platford, 1987). Values for acceptable soil loss within the South African sugar industry generally range from 4 $t.ha^{-1}.year^{-1}$ to 12 $t.ha^{-1}.year^{-1}$ (Platford, 1987) but 20 $t.ha^{-1}.year^{-1}$ was used by Platford (1987) as the acceptable soil loss in the development of the nomograph to determine contour bank spacing in the South African sugar industry. Maintaining soil losses within sustainable limits is paramount in sustaining crop yields from cultivated lands (Russell, 1998b), as illustrated in Figure 2.2. The USLE was employed by Platford (1987) to make predictions of soil loss for all possible combinations of factors and thereafter the results were used to prepare the nomograph.

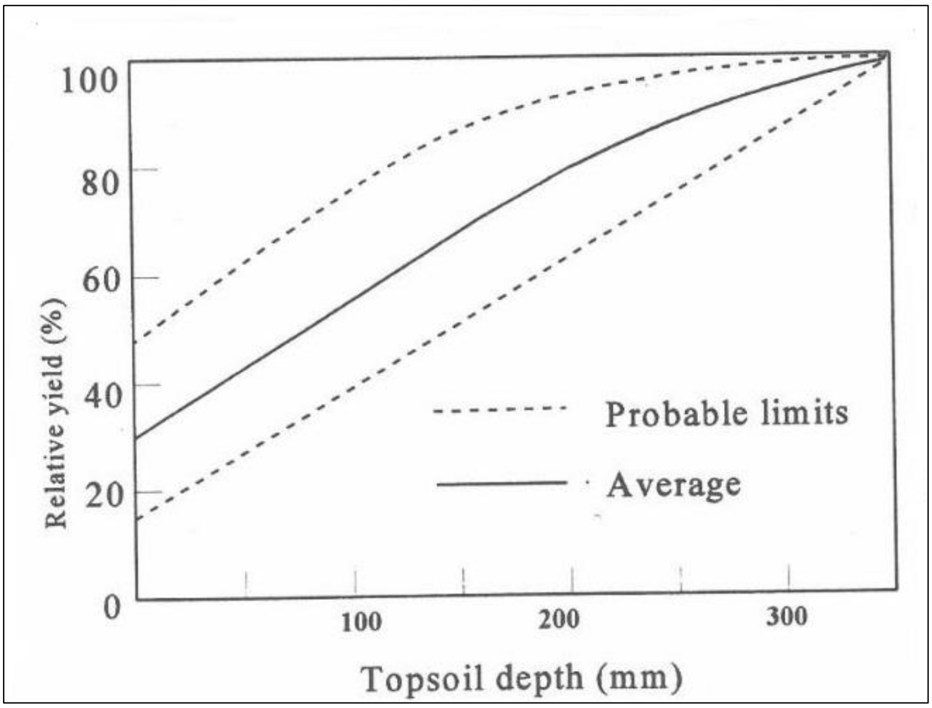

Figure 2.2 Impact of soil loss on crop yield (Russell, 1998b)

Similarly, van Staden and Smithen (1989) developed a nomograph used for the estimation of contour bank spacing for various crops by employing the USLE, as shown in Figure 2.3.

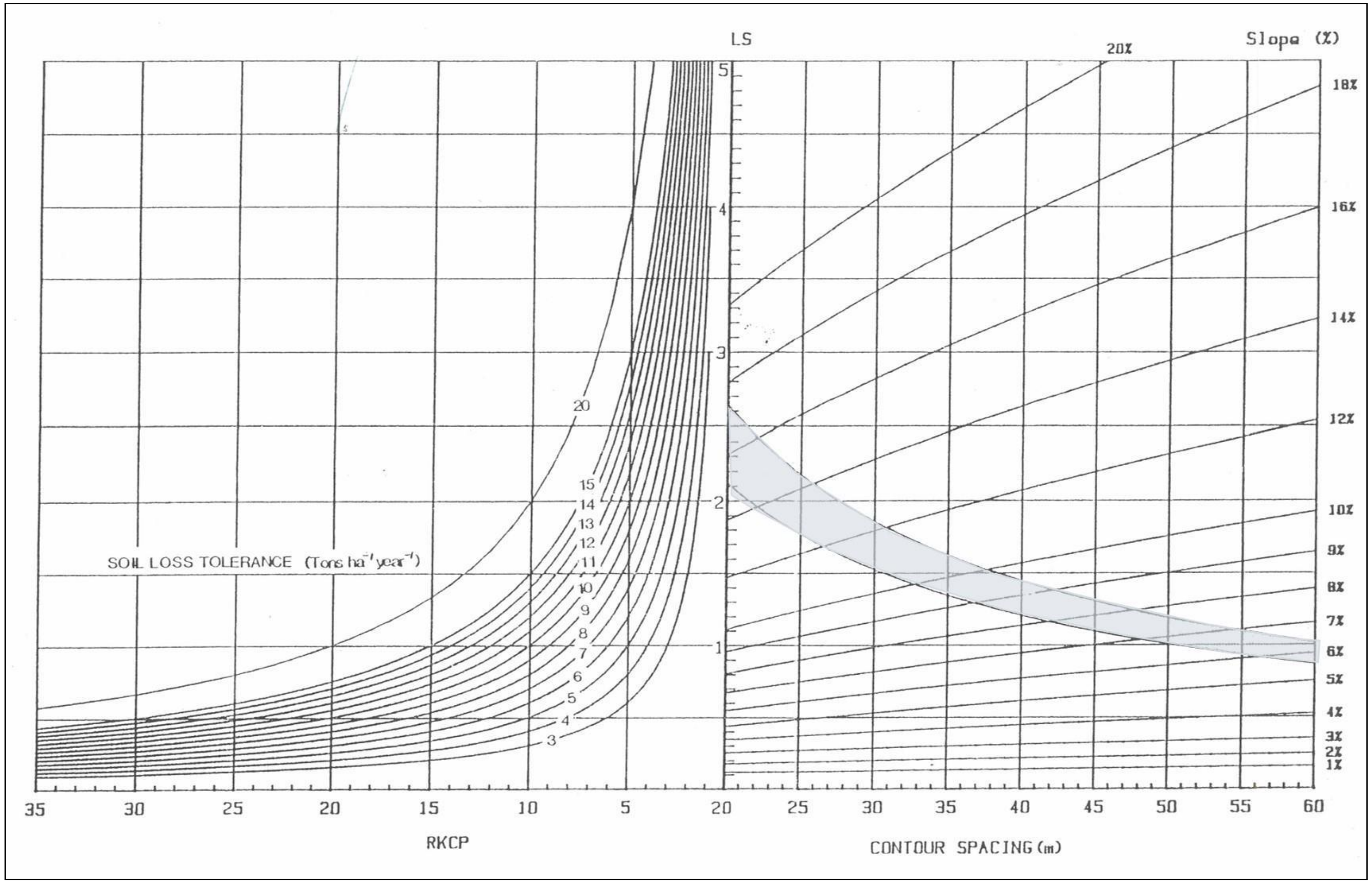

Figure 2.3 Nomograph for contour bank spacing (van Staden and Smithen, 1989)

The nomographs developed by van Staden and Smithen (1989) and by Platford (1987) are different. Differences also exist between these norms and norms employed elsewhere (*e.g.* USA and Australia) as shown in Table 2.2.

Table 2.2 Comparison of South African design norms and norms used in the USA and Australia

Parameter	Design Norm			
	South African Sugar Industry (Platford, 1987; SASA, 2002)	National Soil Conservation Manual for South Africa (van Staden and Smithen, 1989; DAWS, 1990)	Soil and Water Conservation Engineering for USA (Huffman *et al.*, 2013)	Soil Conservation Guidelines for Queensland (Carey *et al.*, 2015)
Maximum slope (%)	40	20	20	10
Sugarcane cover factor, *C*	0.09 – 0.15	0.15 – 0.20	-	-
Maximum horizontal contour spacing (m)	140	60	-	90* 180**

* Single spacing is the computed horizontal interval and should be used where

a) bare fallow cropping systems are present,
b) paddocks are greatly eroding,
c) highly erodible soils are present,
d) contour bank lengths are close to the maximum recommended lengths,
e) maintenance of contour banks is to a minimum, and
f) parallel contour banks with above normal slopes are planned.

** Double spacing is twice the horizontal interval and may be used where

a) cropping systems for high stubble levels in the fallow are employed,
b) soils are stable with minimum erosion, and
c) contour banks are to be built and highly maintained.

2.3.2.1.2 Designing the cross sectional area and slope of contour banks

According to ASABE (2012), contour banks installed on agricultural land should have the capacity to convey the peak rate of runoff anticipated from a 10 year return period, 24 hour storm without overtopping, as a minimum. The 10 year – 24 hour storm caters for effects of moderately intense and moderately infrequent storms which are most likely to cause severe ponding (USDA-ARS, 2008). Design of earth bank contours is relatively simple and involves determination of the correct width, depth, shape and slope to safely discharge the required design discharge (Reinders *et al.*, 2016). Manning's equation for open channel flow is used in the hydraulic design of contour banks and its algorithm is shown in Equation 2.9.

$$v = \frac{1}{n} \times R_h^{2/3} \times S_o^{0.5} \tag{2.9}$$

where

v = flow velocity (m.s^{-1}),

R_h = hydraulic radius (m),

n = Manning's roughness coefficient (s.m$^{-1/3}$), and

S_o = channel slope (m/m).

2.3.2.1.3 Design and sizing of waterways

Waterways are hydraulic structures suitably protected by vegetation or paving and are designed to safely convey the discharge from contour banks to a natural stream or river (SASA, 2002). Vegetated channels are designed for both stability and capacity conditions (Reinders *et al.*, 2016). Stability design is for conditions when vegetation has been recently established or cut short while capacity design is for conditions when the vegetation is fully established in the waterway. The basis for design of waterways is the Manning's equation as shown in Equation 2.9.

2.4 Models for Soil Erosion Estimation

In recent decades, soil erosion by water has become a relevant worldwide issue due to climate change, and as soils are more exposed to erosion for various reasons, including inappropriate agricultural practices and forest fires (Terranova *et al.*, 2009). Consideration should be given to individual rainfall events as they trigger key hydrological responses such as stormflow and sediment yield (Schulze *et al.*, 2011). Erosion models are necessary for soil and water conservation and nonpoint source pollution assessments. According to Amore *et al.* (2004), a number of planning and management theories and formulae have been developed in order to reduce soil loss from catchments. Various models for prediction of erosion are widely documented in literature (*e.g.* Zingg, 1940; Smith, 1941; Wischmeier and Smith, 1978; Renard *et al.*, 1997; Angima *et al.*, 2003; Morgan, 2005; Cohen *et al.*, 2006; Prasannakumar *et al.*, 2012).

Over time, soil erosion models have been developed to increase knowledge, mitigation and degree of resilience regarding erosion processes (Merritt *et al.*, 2003). Erosion and sediment transport models are sub-divided into three main categories, depending on the physical processes simulated, the model algorithms describing these processes and the data dependence of the model. The three erosion model categories are empirical, conceptual and physics-based (Terranova *et al.*, 2009).

Many different soil erosion prediction models are available, ranging across the three model categories described above. The models differ in complexity, the modelled processes, the scale of application, and the assumptions on which they are based (Merritt *et al.*, 2003). Complex deterministic models (*i.e.* conceptual and physics-based models) which represent erosion processes and sediment transport are desirable for the accurate estimation of soil loss. However, use of complex models is limited and not practical due to the requirements of input parameters which are generally only available from research catchments, and the reliance of the complex models on calibration (Lorentz and Schulze, 1995). Simpler models (*i.e.* empirical models) are more robust, thereby providing more stable performances than more complex models (Merritt *et al.*, 2003). Due to these reasons, simple empirical models have proved to be more effective in the provision of sufficient estimates of soil loss for initial planning and design purposes (Lorentz and Schulze, 1995). An overview of these empirical models is presented below.

The USLE (Equation 2.8) was initially developed by Wischmeier and Smith (1965) and further refined by Wischmeier and Smith (1978). The USLE was the first and it is the most important empirical model which calculates the long term average annual soil loss from a field resulting from rill and interrill erosion (Terranova *et al.*, 2009). It has received the most recognition worldwide with the most application and it is the foundation for many other empirical equations (Lorentz and Schulze, 1995). The USLE and its successors, the Revised Universal Soil Loss Equation (RUSLE) (Renard *et al.*, 1991) and the RUSLE2 (USDA-ARS, 2001), are the most used models for prediction of soil erosion (Auerswald *et al.*, 2014).

The RUSLE (Renard *et al.*, 1991) is the revised version of the USLE (Wischmeier and Smith, 1965; Wischmeier and Smith, 1978) and it has been used at numerous spatial scales through sub-division of areas of application into sub-areas with homogeneous factors and combined with GIS applications (Renard *et al.*, 1991). The RUSLE is a set of mathematical equations which estimate average annual soil loss and sediment yields emanating from rill and inter-rill erosion (Ranzi *et al.*, 2012). The RUSLE is applied to estimate soil erosion over extended areas and in different contexts (Renard *et al.*, 1997). Similar to the USLE, the RUSLE does not allow any estimate for deposit and size of sediment for the spatial and temporal distribution of erosion, but it is able to assess mean annual soil loss (Terranova *et al.*, 2009). The algorithm for the RUSLE is similar to the USLE algorithm shown in Equation 8.

The RUSLE2 (USDA-ARS, 2001) model is largely used for official purposes by the United States Department of Agriculture (USDA) - Natural Resources Conservation Services (NRCS) field offices in estimating field erosion (Foster *et al.*, 2001). The RUSLE2 model is founded on the RUSLE that is used in the estimation of average annual sediment yield per unit area based on soil properties, land use, and daily precipitation and temperature data (Sommerlot *et al.*, 2013). According to Foster *et al.* (2003), the RUSLE2 structure is based on the USLE (Wischmeier and Smith, 1965; Wischmeier and Smith, 1978) and RUSLE (Renard *et al.*, 1991) models but the method used to solve governing equations in the RUSLE2 is what differentiates the RUSLE2 from the USLE and the RUSLE. The RUSLE2 encompasses both empirical and process-based science in the prediction of rill and interrill soil erosion by rainfall and runoff (Lloyd *et al.*, 2013). The RUSLE2 algorithm is shown in Equation 2.10 (USDA-ARS, 2008).

$$a_i = r_i k_i l_i S c_i p_i \qquad (2.10)$$

where

a_i = long-term average soil loss for the ith day (t.ha^{-1}.year^{-1}),

r_i = erosivity factor (MJ.ha^{-1}.mm.h^{-1}),

k_i = soil erodibility factor (t.MJ^{-1}.h.mm^{-1}),

l_i = soil length factor,

S = slope steepness factor,

c_i = cover management factor, and

p_i = supporting practices factor.

The RUSLE2 model has a database which is a large collection of input data values (climate, soil, topography and land use) for the USA (USDA-NRCS, 2013). The user of the RUSLE2 model selects entries from the database to describe site-specific field conditions.

Williams (1975), modified the USLE by replacing the rainfall erosivity factor with a stormflow factor and the modification is termed the Modified Universal Soil Loss Equation (MUSLE) (Lorentz and Schulze, 1995). The MUSLE (Williams, 1975) allows for direct prediction of sediment yield hence eliminating sediment delivery ratios and it is applicable for individual storm events (Williams and Berndt, 1977; Hui-Ming and Yang, 2009). Erosive and transport energies are accounted for by the MUSLE through the inclusion of stormflow volume and peak discharge respectively, both of which are projected to change in the intermediate and distant future (Williams and Berndt, 1977). The algorithm for the MUSLE is shown in Equation 2.11 (Hui-Ming and Yang, 2009).

$$Y_{sd} = \alpha_{sy}(Q_v.q_p)^{\beta_{sy}} K.LS.C.P \qquad (2.11)$$

where

Y_{sd} = event sediment yield (t),

α_{sy} = location specific MUSLE coefficient (*i.e.* α_{sy} = 8.934),

Q_v = stormflow volume for the event (m^3),

q_p = event peak discharge, (m^3.s^{-1}),

β_{sy} = location specific MUSLE coefficient (*i.e.* β_{sy} = 0.56),

K = soil erodibility factor (t.h.N^{-1}.ha^{-1}),

L = slope length factor,

S = slope steepness factor,

C = cover management factor, and

P = supporting practices factor.

The MUSLE is embedded in the Agricultural Catchments Research Unit (*ACRU*) (Schulze, 1975) modelling system and it has been verified locally and internationally (Schulze *et al.*, 1995). Additionally, various options are offered for the estimation of the *K*, *L*, *S*, *C*, and *P* factors (Lorentz and Schulze, 1995).

The Soil Loss Estimator for Southern Africa (SLEMSA) model (Equation 2.12) developed by Elwell (1978) was developed mainly with data from the Zimbabwe Highveld for purposes of evaluating erosion emanating from various farming systems which was used to develop recommendation for appropriate conservation measures (Morgan, 2005). The factors employed by SLEMSA were specifically derived for the Zimbabwean Highveld and sub-models have been employed to give best estimates of inter-rill erosion within Zimbabwe and in other areas in southern Africa (Smith, 1999). The SLEMSA is a modelling framework with no mechanistic system description and therefore cannot be universally applied (Smith, 1999).

$$Z = K.X.C \tag{2.12}$$

where

Z = average annual soil loss (t.ha^{-1}),

K = average annual soil loss from a standard field plot (t.ha^{-1}),

X = slope length and steepness factor, and

C = dimensionless crop management factor.

The input parameters for the MUSLE (Williams, 1975) and the RUSLE (Renard *et al.*, 1991) have been extensively researched for southern African conditions (Lorentz and Schulze, 1995; Le Roux *et al.*, 2007). Hence, the MUSLE and RUSLE would be most suitable for application in southern Africa. Generally, climate has the greatest influence on erosion controlling factors followed by the soil parent material while the influence of slope factors are masked by climatic and parent material effects (Manyevere *et al.*, 2016). However, climate aside, crop cover is the most sensitive parameter and it masks the effects of soil erodibility and slope factors on erosion (Gwapedza *et al.*, 2018; Otim, 2018).

2.5 Climate Change Impacts on Design Floods

The frequency of climatic fluctuations, including extreme weather events is expected to increase as a result of changes in climate (Heltberg *et al.*, 2009). Hallegatte (2009) lists land-use planning as one of the sectors in which decisions should take into account climate change since it involves long-term planning, long-term investments and some irreversibility in choices, and it is subjected to changes in climate conditions. There is a likelihood that the frequency of heavy rainfall events has increased over most areas, and the average precipitation may reduce in some regions (Bates *et al.*, 2008). From a global perspective, some areas are expected to experience an increase in runoff while other areas shall have less runoff, and trends in runoff do not necessarily follow the trend in precipitation (Bates *et al.*, 2008). Climate change impacts on hydrological processes have been projected and they vary between regions and seasons (Kundzewicz *et al.*, 2008). Knoesen (2012) projected an increase in both design rainfall and design floods in South Africa as a result of climate change with projections of design floods being larger than those for design rainfall.

According to Smithers (2012), the estimation of design floods will be impacted by the changes and distribution of rainfall and runoff. For instance, climate change impacts on design rainfall must be quantified in order to assess the impact on the estimated design flood. There is thus a need for new and updated methods of design flood estimation so as to account for the impacts of climate change on design flood estimation (Smithers, 2012).

There is a possibility that climate change resulting from increases in temperature and the subsequent impact on rainfall regimes, will lead to increases in the intensity and frequency of extreme rainfall events of both short duration (< 24 hours and down to 5 minutes) and long duration (one day to seven days) and the associated flooding (Schulze, 2011). This would have serious repercussions on the design of hydraulic structures as the failure of such structures is associated with potential economic, environmental and societal negative impacts. Based on studies on climate circulation models, rainfall in the Western Cape and South Africa at large is expected to become more intense and extreme (Du Plessis and Burger, 2015). Generally across South Africa, an increase of up to 10% in short duration design rainfalls may be expected in the intermediate future (2046 – 2065) (Schulze, 2011). This stresses the need for adjustments to future hydrological designs that are based on short duration extreme rainfalls. Schulze (2011) projected increases in design rainfalls of long duration over much of South Africa and the implication is that such increments should be considered in future designs of hydraulic structures. Similar trends have been observed in KwaZulu-Natal by Schulze (2013) and the Western Cape by De Waal *et al.* (2017) and du Plessis and Schloms (2017).

2.6 Discussion and Conclusions

Soil erosion is a serious problem emanating from a combination of agricultural intensification, soil degradation and intense rainstorms. It is estimated that South Africa has an average soil erosion rate of 12.3 $t.ha^{-1}.year^{-1}$ while the estimated rate of soil formation ranges between 0.25 and 0.38 $t.ha^{-1}.year^{-1}$ for each millimetre of top soil. Moreover, when the rate of soil loss is unsustainable, it leads to a reduction in crop yield and hence the need to limit soil losses to sustainable levels. The mechanical means of soil conservation in the South African sugar industry is by use of contour banks/terrace roads and waterways, and the standards and guidelines for the design of soil conservation structures were published by SASA (2002). In addition, strip planting, rotational crops, reduced tillage and other management practices which provide a degree of soil protection should be used in addition to these mechanical means of soil conservation. A nomograph for determining the spacing of soil and water conservation structures in the sugar industry of South Africa was developed by Platford (1987) who used observations from runoff plots and the long term average annual soil loss simulated using the USLE. The USLE estimates annual soil loss, but erosion occurs on an event basis. Likewise, the RUSLE and SLEMSA predict and aggregate the annual soil loss while the RUSLE2 predicts the long-term average soil loss on a given day (*i.e.* the average erosion that would be observed if erosion was measured on that day for a sufficiently long period). The MUSLE, on the other hand, is an event based model capable of predicting sediment yield on an event basis. Thus, it is necessary to develop updated design norms using an event based erosion prediction model since erosion occurs on an event basis, and it is expected that most of the soil erosion occurs from only a few extreme events per year. Hence, the design approach should focus on limiting the erosion during these extreme events. The MUSLE is well suited for this application since it is an event based model and various options for estimation of the MUSLE parameters are available.

Hydrologic design is an important aspect that feeds into the hydraulic design of soil and water conservation structures. Two methods, namely the SCS and Rational Method are used in estimation of design floods and are suited to cultivated lands and natural catchments, respectively. The SCS- SA was specifically adapted for South Africa and is widely used for estimation of design floods from small catchments. The current design norms for the sugar industry specify that soil and water conservation structures be designed for a 10 year return period but are silent on the duration of the rainfall events that are used in their designs, yet a 10 year return period, 24 hour storm is the minimum recommended. Considering that increases in both design rainfall and design floods are anticipated in South Africa as a result of climate change, the 10 year return period currently recommended may not be adequate due to the projected levels of risk and the fact that a few large events are likely to be responsible for the majority of the erosion. In addition, short duration storms with high intensities are more likely to cause erosion than long duration storms with low intensities. Therefore, it would be necessary to incorporate short duration storms (*i.e.* < 24 hours and down to 5 minutes) in the design of soil and water conservation structures. Hence, the impact of rainfall duration, intensity and frequency as well as potential climate change needs to be accommodated in the design of conservation structures. Increasing the return period and decreasing the storm duration would ensure that the projected extreme events likely to cause erosion are adequately accommodated in the updated design norms, thereby maintaining soil losses to sustainable levels.

Climate has the greatest influence on erosion controlling factors followed by the soil parent material, while the influence of slope factors is masked by climatic and parent material effects. The nomograph for the design of soil and water conservation structures in the sugar industry does not include any regional variations of climate and the impact on soil erosion and runoff. Therefore, it is imperative to incorporate regional variations in climate in the updated design norms for the design of soil and water conservation structures.

The design of conservation terraces involves two aspects, *i.e.* spacing and hydraulic design. Contour bank spacing can be achieved by applying one of two methods, namely the sustainable soil loss method and the vertical interval method, of which the former is the preferred method. The sustainable soil loss method employs a sheet and rill erosion prediction tool to determine contour spacing. The simulation conducted by Platford (1987) generated various values used in the construction of the nomograph for the design of soil conservation structures in the sugar industry. However, most of the soil loss values used in the construction of the nomograph for the design of soil conservation structures in the sugar industry of South Africa exceed the 20 $t.ha^{-1}.year^{-1}$ fixed by Platford (1987), which in itself exceeds the acceptable soil loss value of 9 $t.ha^{-1}.year^{-1-}$ for heavy deep soils underlying topsoil proposed by van Staden and Smithen (1989). The soil loss of 20 $t.ha^{-1}.year^{-1}$ is not sustainable thus giving unsustainable contour bank spacing for soil losses in excess of 9 $t.ha^{-1}.year^{-1}$. In addition, the 20 $t.ha^{-1}.year^{-1}$ fixed by Platford (1987) is in excess of the 5 – 10 $t.ha^{-1}.year^{-1}$ based on 250 mm soil depth for sustainable crop production documented by Matthee and Van Schalkwyk (1984). Hence, the 5 – 10 $t.ha^{-1}.year^{-1}$ based on 250 mm soil depth for sustainable crop production is recommended as the sustainable soil loss threshold. The nomograph employed in the South African sugar industry also deviates from the nomograph contained in the National Soil Conservation Manual (*e.g.* maximum slope, cover factors for sugarcane and maximum contour spacing) and norms employed in the USA and Australia. The design norms for soil and water conservation structures in the sugar industry also advocate for specific designs whenever slopes are less than 3% or greater than 30% although the design nomograph used in the sugar industry caters for slopes up to 40%. Some slopes in the sugar production industry exceed 40% and yet the nomograph has a maximum slope of 40% and cannot be used to design structures on land were slopes are greater than 40% or less than 3%. The 40% slope is also greater than the 20% maximum slope contained in the National Soil Conservation Manual (van Staden and Smithen, 1989). Hence, these anomalies need to be revised and harmonised in the updated design norms for the design of soil and water conservation structures.

The nomograph used in the local sugar industry further assumes strip planting which is generally no longer practiced in South Africa. Failure to practice strip cropping exposes the soils to erosion and hence recommendations for practices like mulching would limit the amount of soil loss.

Accidental and runaway fires are common occurrences in sugarcane harvesting in South Africa and often spread over entire hillsides, thereby exposing the land under sugarcane production to potential erosion (SASRI, 2014). Such an unforeseen occurrence is not accounted for in the design norms for soil and water conservation structures in the sugar industry and should be considered in future design norms.

Crop rotation is important in sugar production, ensuring soil fertility and reduction of pests and diseases, yet this important practice is not included in the design norms for soil and water conservation structures in the sugar industry. During the rotation period, the cover factor of the rotation crops is different to the sugarcane cover factors. Hence, some practices allowed during sugar production like spraying pests and diseases and burning at harvest may not be performed as a result of crop rotation. The design nomograph used in the sugar industry does not include vulnerability during break cropping where the cover may be reduced as a result of field rejuvenation and replanting of sugarcane. The sugarcane cover factors in the National Soil Conservation Manual range between 0.15 and 0.20 (DAWS, 1990) while the factors in the sugar industry design norms range between 0.09 and 0.15 (Platford, 1987).

In conclusion, there is a need to accommodate climate change variations, significant events of soil erosion, production and management practices, unforeseen occurrences which may occur, and regional differences in climate, soils and slopes in future design norms for soil and water conservation structures in the sugar industry of South Africa.

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3 ASSESSMENT OF RELATIONSHIPS IN RUNOFF, PEAK DISCHARGE AND SEDIMENT YIELD AT THE LA MERCY CATCHMENTS LOCATED IN SOUTH AFRICA UNDER BAREFALLOW CONDITIONS AND SUGARCANE PRODUCTION

Part of this Chapter was published as follows:

Otim, D, Smithers, JC, Senzanje, A and van Antwerpen, R. 2019a. Assessment of trends in run-off and sediment yield from catchments under sugarcane production and management practices*. *International Sugar Journal* 121 (1443): 216-219.

Abstract

Rainfall plays a dominant and driving role on hydrological processes. Runoff generally increases non-linearly with rainfall and rainfall-runoff models are very sensitive to rainfall input. Errors in rainfall data are magnified in simulated runoff, hence the need for accurate and consistent observed rainfall and runoff records in order to verify acceptable runoff simulations. The main objective of this study is to increase understanding of hydrological and soil erosion processes from bare fallow and catchments under various sugarcane production management practices. The study area was located at La Mercy, KwaZulu-Natal in South Africa on the site that now hosts the King Shaka International airport. It consisted of four research Catchments namely 101, 102, 103 and 104 established and monitored by the former South Africa Sugar Experiment Station (SASEX). The catchment areas ranged from 2.7 ha to 6.6 ha while the slopes ranged from 12% to 29%. The data consists of breakpoint digitised rainfall data, daily rainfall and runoff records for the period 1978 – 1995, peak discharge and sediment yield data for the period 1984 – 1995 for the La Mercy catchments which were checked for errors by Smithers *et al.* (1996). Daily rainfall data for the period 1978 – 1995 from two weather stations (*i.e.* La Mercy Airport and Tongaat) close to the La Mercy catchments were obtained from the daily rainfall database developed by Lynch (2003). Relationships between rainfall from the La Mercy catchments and the two nearby stations, and daily rainfall and runoff from the La Mercy catchments were assessed and analysed. A consistency test conducted between the daily rainfall records from the La Mercy catchments and the two nearby stations showed that the rainfall data were consistent and may be used in further analyses with confidence. Comparisons between daily rainfall and runoff data from the four La Mercy catchments showed that some inconsistencies in the records existed and they were attributed to loss of some records. Excluding the inconsistent data improved the association between rainfall and runoff, hence generating a clean data set. Under bare fallow conditions, runoff was found to be inversely proportional to the length of overland flow and a link between the soils' runoff potentials on the generation of runoff was evident although the effect of catchment slope was not evident. Hence, it appears the effects of overland flow distance and soils' runoff potentials masked the effects of catchment steepness on runoff generation. During periods when the catchments were under sugarcane, the effects of tillage were evident with the catchment under minimum tillage registering the least runoff compared to those under conventional tillage. In addition, runoff increased with increases in the overland flow path although the effects of soil type, conservation structures and catchment slope on runoff were not evident. It is postulated that crop cover and other management practices mask their effects. Peak discharge was observed to increase with increases in rainfall intensity, runoff volume and catchment area and this is consistent with observations made by Schmidt and Schulze (1984), and Schulze (2011). With respect to sediment yield, runoff volume and peak discharge had a large impact on the generation of sediment yield. Relatively few rainfall and runoff events were responsible for the generation of sediment yield. In general, low soil erodibility, cover and management practices had a greater effect on the reduction of sediment yield than conservation structures which is in agreement with observations made by Maher (2000). On the other hand, the effect of catchment steepness on sediment yield was not evident and it is postulated that soil erodibility and cover and management practices neutralise the effects of catchment steepness on sediment yield production.

Keywords: hydrological response, bare fallow, sugarcane production, consistency, La Mercy catchments, South Africa

3.1 Introduction

Rainfall is a dominant and driving variable in initiating and sustaining most hydrological processes (Schulze *et al.*, 1995; Schulze and Smithers, 1995). The relationship between rainfall and runoff is non-linear and an increasing fraction of rainfall is converted to runoff as a catchment becomes wetter (Schulze *et al.*, 1995) with the coefficient of determination (R^2) tending to unity for wetter catchments. Rainfall-runoff models are very sensitive to rainfall input and any errors in rainfall data are magnified in simulated runoff. Therefore, accurate and consistent rainfall records are important in ensuring acceptable runoff simulations (Schulze, 1995; Schulze and Smithers, 1995). Furthermore, rainfall is the most temporally and spatially variable element of climate in relation to the production of runoff, thus accurate estimates of rainfall are a basic requirement for hydrologic studies (Schulze, 2011). Variations in rainfall are influenced by topography, physiographic features and prevailing synoptic conditions. Inconsistencies in rainfall data are often caused by relocation of rain gauges, changing instrumentation, human error, or a number of environmental factors which may influence rainfall recordings (De Waal *et al.*, 2017). According to Searcy and Hardison (1960), and Reddy (2005), consistencies in hydrologic data (*e.g.* rainfall, runoff and sediment data) can be checked with a double-mass curve. A double mass curve is a plot of cumulative data of one variable against the cumulative data of a related variable and a linear correlation (*i.e.* slopes of regression lines and R^2 close to unity) between the variables represents consistency in the data (Searcy and Hardison, 1960).

This research reported in this paper is a component of a wider study whose aim is to update design norms for soil and water conservation structures in the sugar industry in South Africa. The objective of this study was to increase understanding of hydrological and soil erosion processes from bare fallow and catchments under various sugarcane production management practices. This was done by assessing the relationships between observed rainfall, runoff, peak discharge and sediment yield data at the La Mercy catchments under bare fallow conditions and sugarcane production and for different management practices.

3.2 Impact of Management Practices on Hydrological Responses under Bare Fallow and Sugarcane Production Conditions

Runoff from bare soils is generally greater in magnitude than runoff from mulched soils (McPhee *et al.*, 1983). Smithers *et al.* (1996) and Maher (2000) reported that catchment runoff response from rainfall events is dependent on interactions between rainfall intensity, antecedent soil moisture conditions and land cover. According to McPhee *et al.* (1983), the initial abstraction, also known as the depth of water which infiltrates into the soil profile before commencement of runoff, and the average infiltration depth during runoff events greatly influence the amount of runoff generated. On the other hand, peak discharge from a catchment depends on catchment slope, runoff volume, rainfall depth, rainfall intensity and area of catchment (Schulze, 2011). In general, peak discharge from a catchment is closely related to the runoff volume generated from that catchment (Schmidt and Schulze, 1984).

Under bare fallow conditions, catchment steepness and distance of overland flow influence the initiation of runoff (Platford and Thomas, 1985). Increases in overland flow distance correspond to reductions in runoff because additional time is allowed for infiltration losses to occur (Stomph *et al.*, 2002). Bare fallow conditions are associated with high runoff volumes, and hence it is recommended to retain as much crop cover as possible and to disturb the soil as little as possible in order to reduce generation of runoff and thus to limit soil erosion (Maher, 1990).

Runoff from cultivated lands is frequently controlled and managed through the use of agronomic, soil management and mechanical means and all approaches of soil conservation should be used in the management of runoff and to limit soil loss from cultivated lands (Reinders *et al.*, 2016). Generally, crop cover and management practices reduce runoff to a greater extent than soil and water conservation structures (Maher, 1990). Nonetheless, conservation structures are necessary to reduce both runoff and erosion after the crop cover has been removed. According to USDA-ARS (2013), management of land cover impacts on runoff in various ways. For example, tillage practices which mechanically disturb soil surfaces reduce runoff on soils with no biomass compared to soils left undisturbed for several years. Tillage induced roughness has a significant impact on runoff and erosion (Takken *et al.*, 2001) and the rougher the soil surface, the greater the infiltration thereby reducing runoff and erosion from the surface (Lavee *et al.*, 1995; Battany and Grismer, 2000). Rough surfaces have many depressions and barriers and, when it rains, they trap water and sediment hence resulting in lower erosion rates than smooth surfaces under similar conditions (Lorentz and Schulze, 1995). Studies conducted by Haywood and Mitchell (1987) showed that minimum tillage practices significantly reduce runoff compared to conventional tillage practices. Conservation tillage practices (*e.g.* no tillage, reduced tillage and mulch tillage) inhibit surface runoff through increased contact time of water on the surface thereby leading to more water infiltration and reduced runoff (Mupangwa *et al.*, 2007). Maher (1990) stresses the need for maintenance of crop cover through strip planting and disturbing the soil as little as possible by minimum tillage so as to minimise runoff generation, particularly on steep catchments.

3.3 Impact of Land Use Practices on Sediment Yield under Bare Fallow and Sugarcane Production Conditions

Exposure of a bare soil surface to raindrop impact and surface runoff often leads to erosion (USDA-ARS, 2008). Soil texture is significant in influencing erosion (Manyevere *et al.*, 2016) and, in South Africa, soil parent material erodibility is the overriding erosion risk factor and not the slope gradient as established in the USA (Le Roux *et al.*, 2007). High sediment yield is not only slope-related, but crop cover is important in its generation, *i.e.* a catchment with a relatively flat slope and a relatively poor crop cover generates more sediment yield than a catchment with a steep slope and good crop cover (Lorentz *et al.*, 2012). Sediment yield, which is also referred to as the average annual erosion for an entire overland flow path, is the ratio of the average annual sediment amount leaving the overland flow path to the overland flow path length (*i.e.* $mass.width^{-1}.year^{-1}$) (USDA-ARS, 2013). According to Foster *et al.* (2003) and USDA-ARS (2008), cultural and supporting land use practices are used to control soil loss. Cultural practices, also known as crop cover and management practices, include vegetative cover, crop rotations, conservation tillage and applied, mulch while supporting practices (*i.e.* conservation structures) include contouring, strip cropping and terraces (USDA-ARS, 2008; USDA-ARS, 2013). Similar to runoff reduction, cover and management practices reduce soil loss to a greater extent than conservation structures in sugarcane fields (Maher, 1990; Maher, 2000). However, crop cover is more effective in reducing soil loss than runoff (*i.e.* crop cover acts as a buffer which reduces the impact of falling raindrops dramatically) (Maher, 1990). In general, conservation structures become important when the crop cover is removed at harvest and at planting (Maher, 2000).

3.4 Data and Methods

This study utilises historical information for the period 1978 – 1995 from research catchments under bare fallow conditions and sugarcane production and for different management practices. A description of the data and methods employed in the assessment and analysis of data relationships at the La Mercy catchments is contained in the underlying sub sections.

3.4.1 Study area

The study area is located at La Mercy, 28 km north of Durban in South Africa on the site that now hosts the King Shaka International airport. The research catchments were established by the South African Sugarcane Research Institute (SASRI), formerly SASEX, and were monitored under bare fallow and various sugarcane management practices. However, it was impossible to maintain all four catchments completely and constantly under bare fallow conditions due to weeds, hence the catchments were often slashed, harrowed and ploughed (Platford and Thomas, 1985). The experiment comprised four small catchments numbered from south to north, with Catchment 101 the southernmost catchment and Catchment 104 the northernmost catchment (Platford, 1979; Platford and Thomas, 1985; Haywood and Schulze, 1990; Maher, 1990; Haywood, 1991; Maher, 2000), as shown in Figure 3.1. Catchment characteristics and management practices are summarised in Table 3.1 and soil types in Table 3.2.

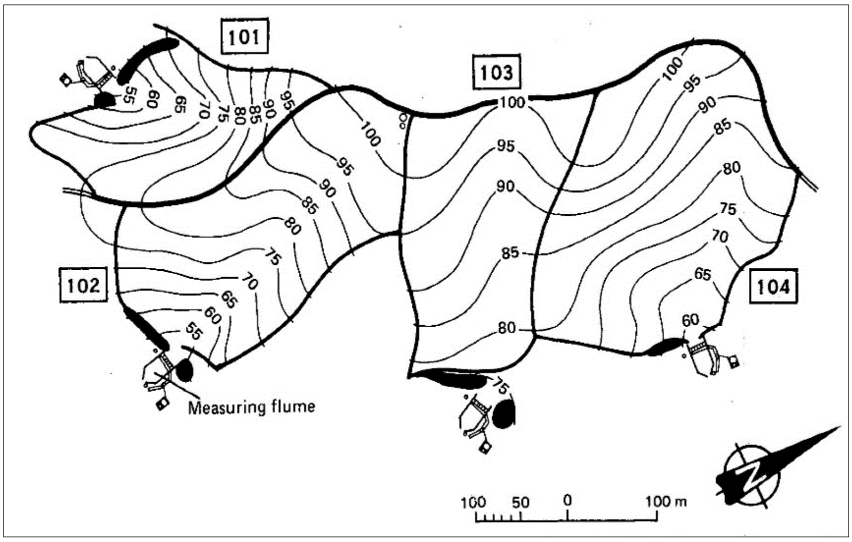


Figure 3.1 Layout of the La Mercy catchments (Platford and Thomas, 1985)

Table 3.1 Characteristics and management practices of the La Mercy catchments (after Platford and Thomas, 1985)

Location/ Practice	Catchments			
	101	102	103	104
Latitude (^{o},')	29^{o} 63' E	29^{o} 63' E	29^{o} 63' E	29^{o} 63' E
Longitude (^{o},')	31^{o} 07' S	31^{o} 07' S	31^{o} 07' S	31^{o} 07' S

Location/ Practice	Catchments			
	101	102	103	104
Altitude	75	75	90	80
Area (ha)	2.7	4.7	4.4	6.6
Catchment Slope (%)	29	21	12	17
Catchment width (m)	160	155	150	325
Catchment length (m)	260	375	330	380
Period of bare fallow	January 1978 to August 1984	January 1978 to August 1984	January 1978 to August 1984	January 1978 to December 1985
Date of sugarcane planting	September 1984 to December 1995	September 1984 to December 1995	September 1984 to December 1995	January 1986 to December 1995
Method of land preparation	Minimum tillage[1]	Conventional tillage[2]	Conventional tillage[2]	Conventional tillage[2]
Method of harvesting	Strip	No strip	No strip	Strip, and with two additional strips permanently under bare fallow and harrowed frequently
Structures	Spill over roads	Water conveying terraces	No structures	Water conveying terraces

Location/ Practice	Catchments			
	101	102	103	104
Grass waterways	Yes	Yes	No, but has natural depression sown with *Eragrostis curvula* before planting	Yes
Equipment used in the construction of conservation structures	D5D caterpillar bulldozer	Two-wheel drive John Deere tractor pulling reversible two-disc plough	None	Two-wheel drive John Deere tractor pulling reversible two-disc plough

[1] Minimum tillage is the practice of reduced soil disturbance when the land is being prepared for planting (SASRI, 1998).

[2] Conventional tillage is the standard practice of ploughing with a disc, single or various disc harrows, a spike-tooth harrowing and surface planting (Morgan, 2005).

Table 3.2 Soil type distributions in the La Mercy catchments (after Platford and Thomas, 1985; Smithers *et al.*, 1995; Smithers *et al.*, 1996; van Antwerpen *et al.*, 2013)

Soil Form*	Soil Series	Soil Code	Soil Depth (m)	Soil texture	Runoff Potential**	Infiltration Potential**	Erosion Hazard Rating	Area per Catchment (%)			
								101	102	103	104
Hutton	Clansthal	Hu24	> 1.0	Sandy loam	Moderately low	Excessive to good	Moderate	0	0	0	10
Arcadia	Rydalvale	Ar30	0.3 – 0.9	Clay	Moderately high to high	Fair to poor	Low	71	97	98	37

Swartland	Swartland[#]	Sw31	0.1 – 0.6	Sandy clay	Moderately high to high	Fair to poor	High	29	3	2	53

* MacVicar *et al.* (1977)

[#] Susceptibility to erosion increases after the sandier A horizon has become water saturated.

** Runoff potential increases with decreasing soil infiltration rates.

3.4.2 Data

A daily data set of observed rainfall and runoff depth, checked for errors with clarification of probable inconsistencies in observed data between catchments and collated into the *ACRU* composite hydrometeorological data file format, was extracted from studies conducted by Smithers *et al.* (1996). According to Platford (1988), Maher (1990) and Platford and Bond (1996), some records from the major storms which occurred in early 1984 as a result of cyclone Demoina and the September 1987 floods were lost due to equipment failure. Various complex factors involved in hydrological and sediment production cycles made it difficult to obtain their absolute responses and ratings of runoff and sediment yield within the first two years of planting sugarcane (Platford and Thomas, 1985). Under bare fallow conditions, sampling equipment were frequently washed away or completely silted up thereby leading to a lack of records (Maher, 1990). Haywood (1991) further noted that the measuring equipment were poorly calibrated. In addition, storms which occurred after harvesting would cause residue to block the entrance of measuring flumes thereby resulting in reduced flows into the collecting tanks. Theft and vandalism of the rainfall intensity gauges was also a big problem and a number of records from the automatic recorders were affected (Maher, 1990). Furthermore, numerous sediment yield records were incomplete due to frequent blockages of the Coshocton wheel (Platford and Thomas, 1985), and Maher (1990) only analysed four events of complete sediment yield records. The data comprise rainfall intensity, daily observed rainfall and runoff for the period 1978 – 1995, peak discharge and sediment yield data for the period 1984 – 1995, daily maximum and minimum temperature, and class A pan evaporation data for the period 1978 – 1995. Historical information on the management practices at the La Mercy catchments for the period 1978 – 1988 was also obtained from studies conducted by Haywood (1991). In addition, daily rainfall data for two nearby weather stations (*i.e.* La Mercy Airport and Tongaat) within 2 km to 7 km of the La Mercy catchments respectively for the period 1978 – 1995 were extracted from the Lynch daily rainfall database using the Kunz extraction utility (Lynch, 2003; Kunz, 2004). The location of the stations are shown in Figure 3.2.

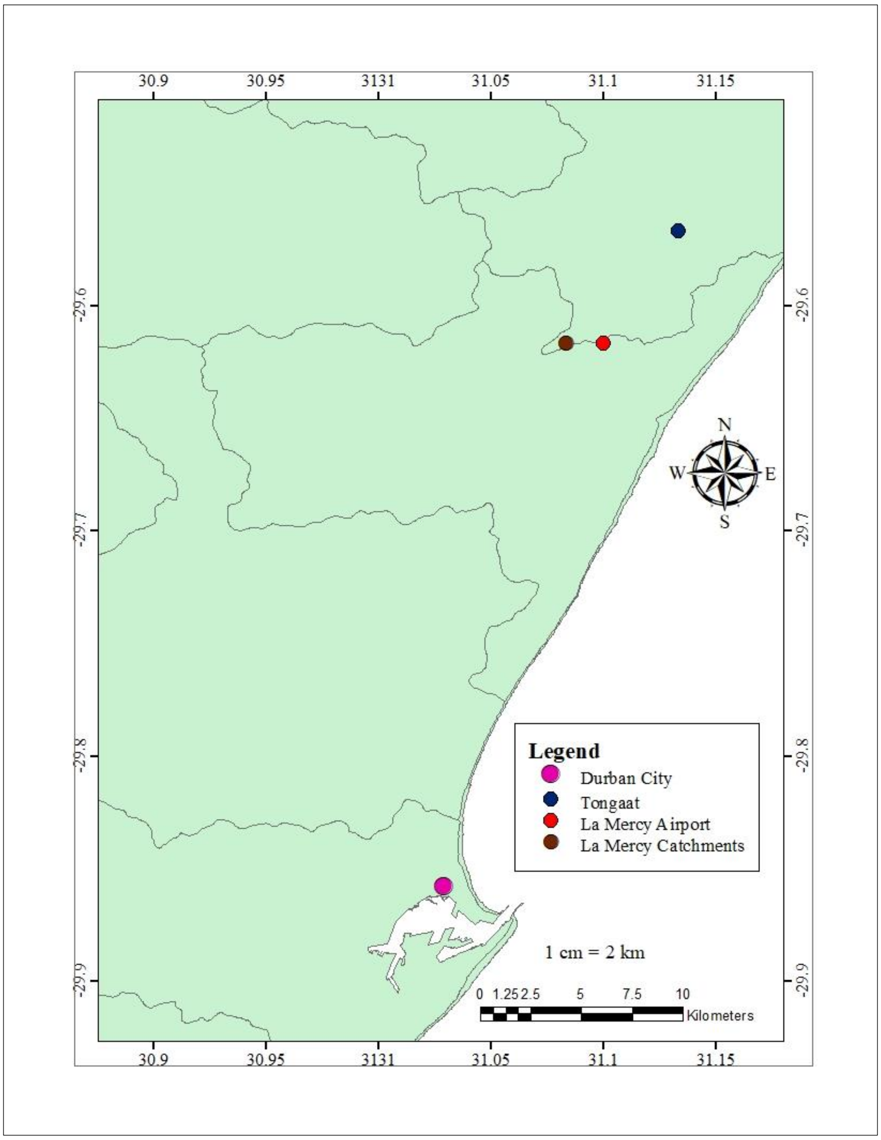


Figure 3.2 Weather stations within the vicinity of the La Mercy catchments

3.4.3 Assessment of data relationships

Smithers *et al.* (1996) conducted a preliminary assessment of the relationships and consistencies in the observed rainfall and runoff data at the four La Mercy catchments. Runoff data from Catchment 104 was found to be inconsistent compared to runoff data from Catchments 101, 102 and 103. It was therefore recommended that the record of calibration of the runoff monitoring structure in Catchment 104 be investigated but it appears that the calibration records were never subsequently investigated. Given that the site for the former La Mercy catchments currently houses King Shaka International airport, it was not possible to investigate the calibration records. Nevertheless, a consistency test between cumulative rainfall from the La Mercy catchments and cumulative rainfall from two surrounding base stations (*i.e.* La Mercy Airport and Tongaat) was conducted. In addition, a rainfall consistency test was conducted with daily rainfall from each of the two base stations. Finally, an assessment of relationships between daily rainfall and daily runoff, daily peak discharge and sediment yield from the La Mercy catchments was conducted in order to identify probable errors in records of observed rainfall, runoff, peak discharge and sediment yield.

3.5 Results and Discussion

This section contains the results and discussion of rainfall consistency, comparisons of rainfall and runoff depths, assessment of runoff relationships, assessment of relationships in peak discharge and sediment yield with rainfall and runoff at the four La Mercy catchments.

3.5.1 Rainfall consistency test

A double mass plot of cumulative rainfall for each base station (*i.e.* La Mercy Airport and Tongaat) for the period 1978 – 1995 against cumulative rainfall for the La Mercy catchments for the same period generally shows that the rainfall from the La Mercy catchments is consistent, as illustrated in Figure 3.3. However, plots for daily rainfall from the two base stations for the period 1978 – 1995 against daily rainfall for the La Mercy catchments show some large daily rainfall from the La Mercy catchments without rainfall from the other stations and vice-versa as indicated in Figure 3.3. Furthermore, the daily rainfall at the La Mercy catchments was generally higher than daily rainfall at the two base stations (*i.e.* slopes of regression lines < 1.0) as shown in Figure 3.3. The differences in magnitude between daily rainfall from the La Mercy catchments and daily rainfall from La Mercy Airport and Tongaat could be attributed to differences in temporal and spatial distribution of rainfall between the stations. Considering that the cumulative rainfall for the La Mercy catchments is consistent with the cumulative rainfall from each of the base stations, the rainfall data for the La Mercy catchments can be used for further analyses with confidence.

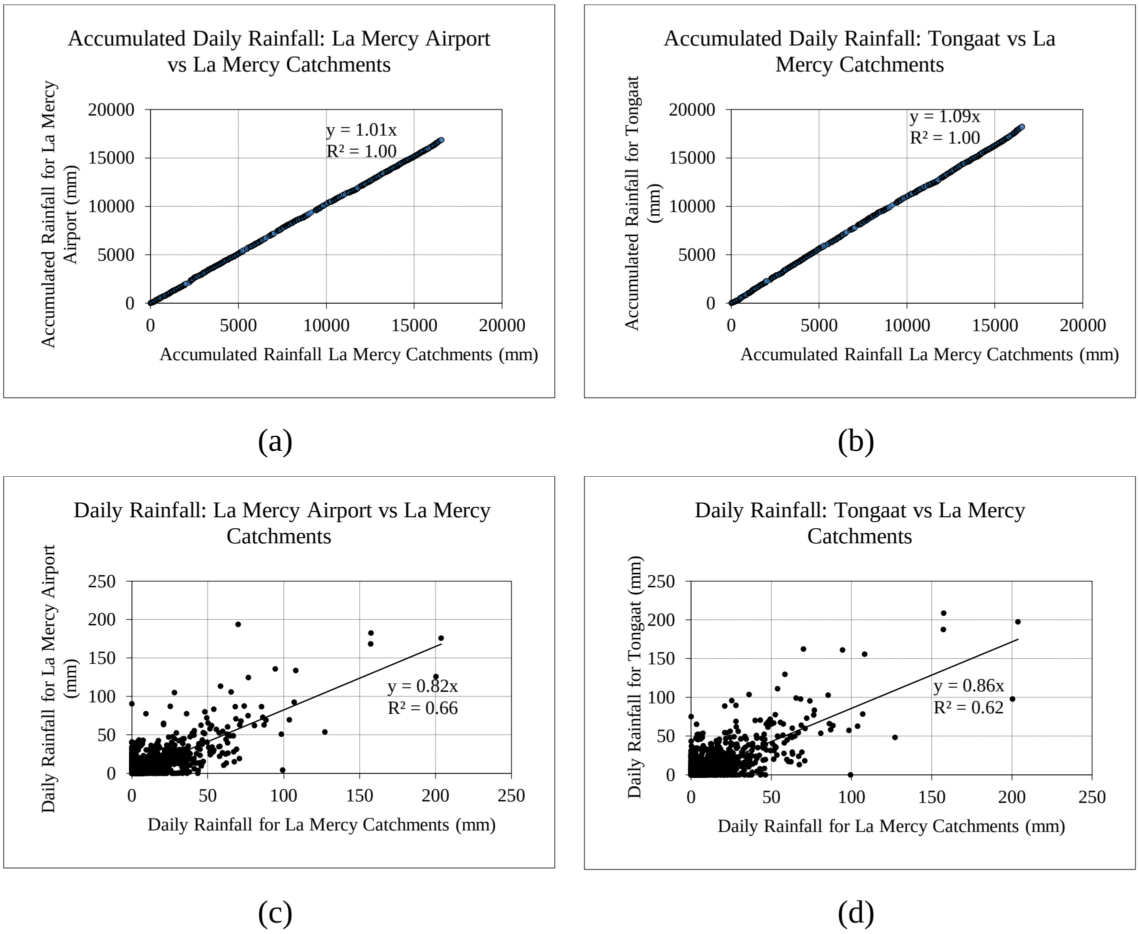


Figure 3.3 (a, b) Accumulated daily and (c, d) daily rainfall consistency plots: Base stations vs La Mercy

3.5.2 Daily runoff versus daily rainfall

Plots of observed daily runoff against daily rainfall for the La Mercy catchments for both bare fallow and sugarcane cover conditions are shown in Figure 3.4 and Figure 3.5 respectively. From the plots, it is evident that the association between runoff volume and rainfall is poor and various inconsistencies in rainfall and runoff depths exist at the La Mercy catchments. Further scrutiny of the 7 day antecedent rainfall records summarised in Appendix 3.1 show that the catchments were relatively wet prior to receiving rainfall greater than or equal to 25 mm. Hence, the recorded runoff depths were not plausible. The coefficient of determination (R^2) for Catchments 101, 102, 103 and 104 under bare fallow conditions are 0.103, 0.158, 0.245 and 0.306 respectively while the respective R^2 values under sugarcane land cover conditions are 0.425, 0.612, 0.605 and 0.707. The inconsistencies in the records include:

(a) runoff depths equal to zero but with rainfall greater than or equal to 25 mm and the 7 day antecedent rainfall showing that the catchments were wet,

(b) rainfall depth equal to zero but runoff volume greater than zero, and

(c) runoff depth exceeding rainfall for some days.

The inconsistencies between runoff and rainfall could be attributed to loss of some records as documented by Platford and Thomas (1985), Maher (1990) and Haywood (1991) or a phasing problem where daily rainfall and runoff were recorded on different days even though the duration of the event was < 24 h. The inconsistent records for which the 7 day antecedent rainfall records show that the catchments were wet together with the respective maximum rainfall intensities are shown in Appendix 3.1.

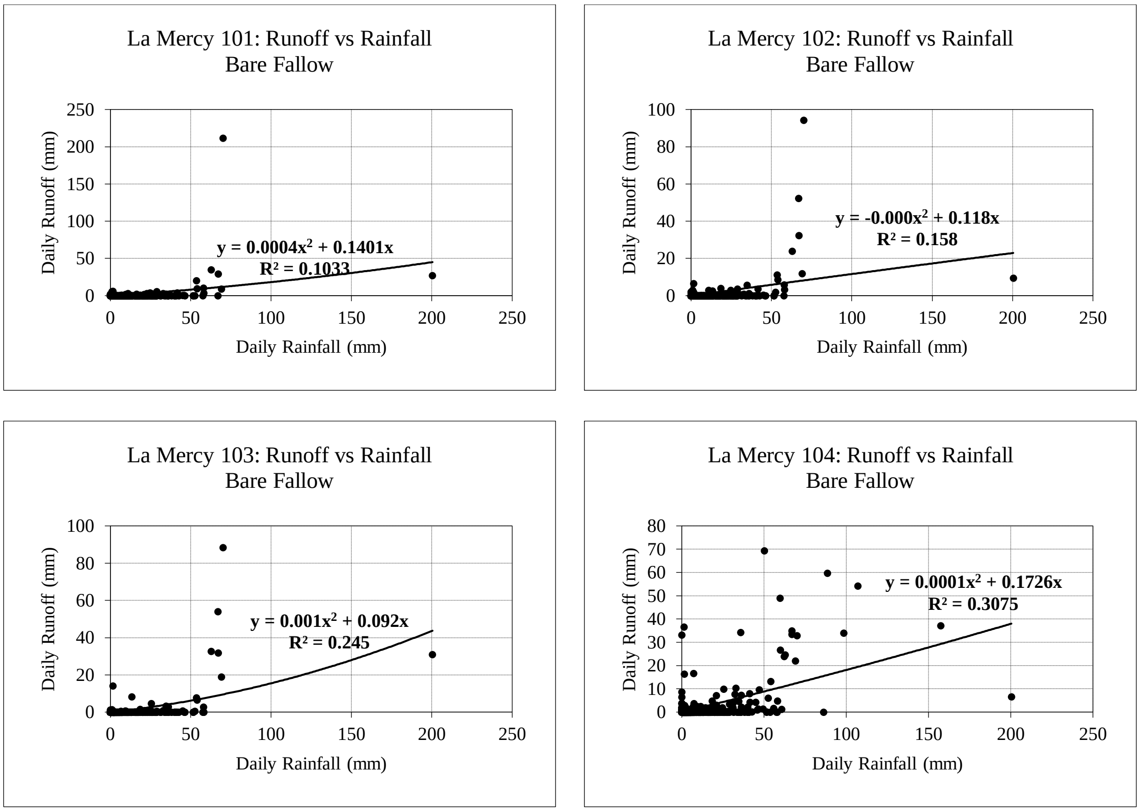


Figure 3.4 Daily runoff vs Daily rainfall: La Mercy catchments, Bare fallow conditions

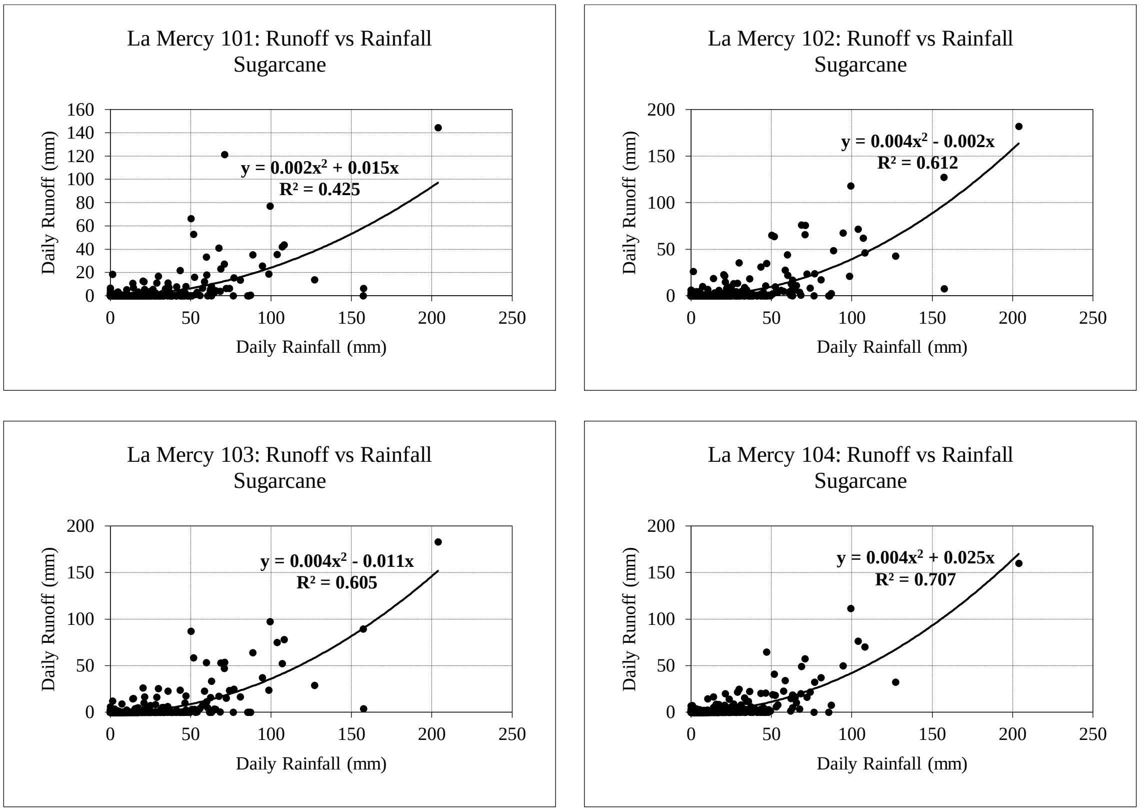


Figure 3.5 Daily runoff vs Daily rainfall: La Mercy catchments, Sugarcane cover

3.5.3 Event rainfall versus event runoff

In order to improve the consistency between runoff and rainfall, daily rainfall and runoff data were further scrutinised and corrected for phasing by moving rainfall and runoff recorded on different days to the same day. However, the inconsistent events presented in Section 3.5.2 which were not affected by phasing problems were excluded, as detailed in Appendix 3.1 and plots of runoff vs rainfall made with consistent events only are shown in Figure 3.6 and Figure 3.7. The excluded inconsistent records were runoff depths equal to zero but with rainfall greater than or equal to 25 mm, rainfall depth equal to zero but runoff depth greater than zero and runoff depths greater than rainfall.

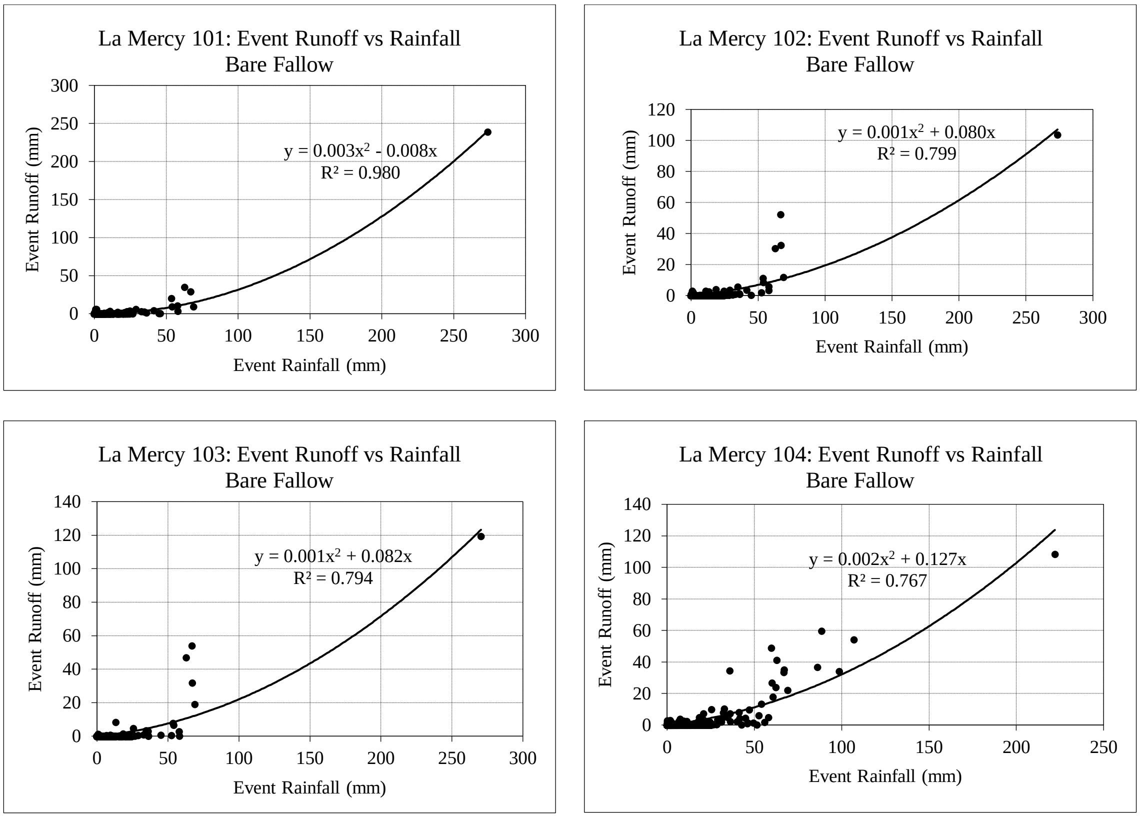


Figure 3.6 Observed runoff vs rainfall for discrete events: La Mercy catchments, bare fallow

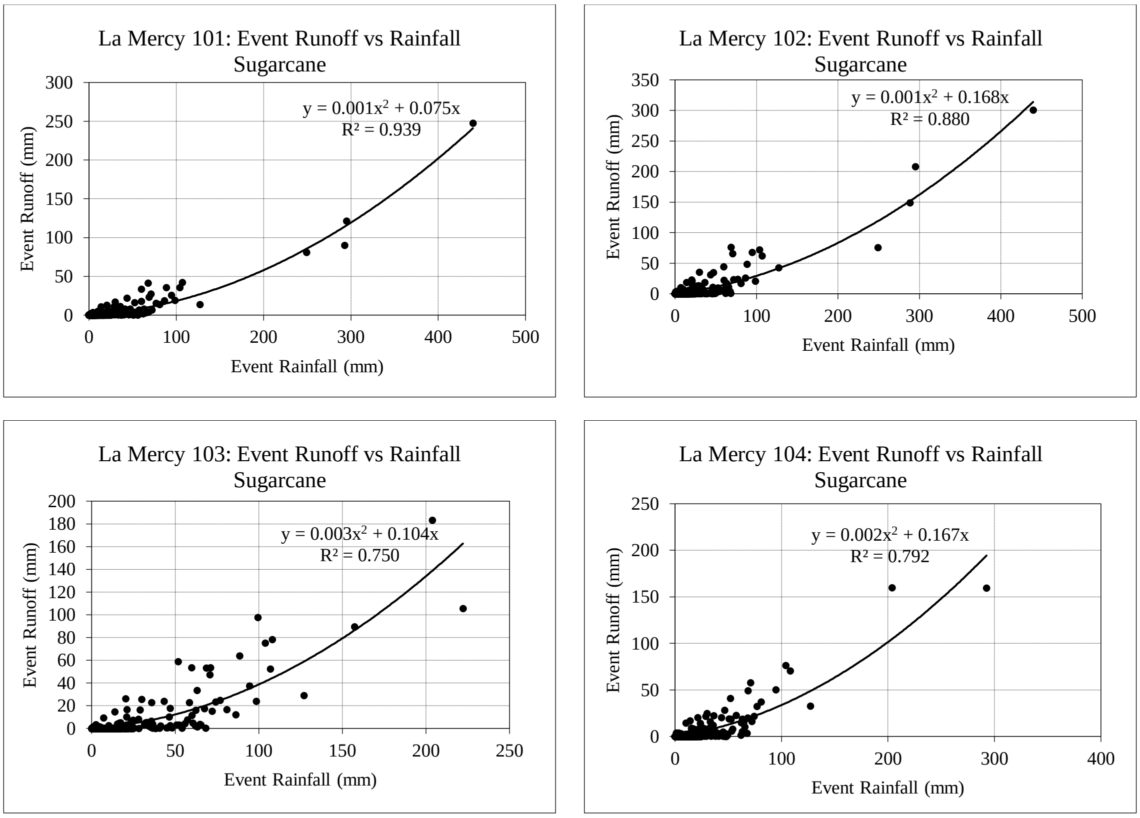


Figure 3.7 Observed runoff vs rainfall for discrete events: La Mercy catchments, sugarcane cover

From Figure 3.6 and Figure 3.7, it is evident that correction for phasing problems and exclusion of inconsistent runoff and rainfall events greatly improved the association between runoff and rainfall as depicted by the R^2 values. Under bare fallow conditions, the R^2 coefficients are 0.980, 0.799, 0.794 and 0.767 for Catchments 101, 102, 103 and 104 respectively while the respective R^2 coefficients under sugarcane cover conditions are 0.939, 0.880, 0.750 and 0.792.

3.5.3.1 Accumulated runoff volume

Accumulated daily runoff plots depicting relationships of runoff across the La Mercy catchments under bare fallow and sugarcane cover are shown in Figure 3.8 and Figure 3.9 respectively, followed by an analysis and discussion of the relationships. For purposes of comparison, the accumulated runoff plots were restricted to the periods under which all the four catchments were under bare fallow conditions and sugarcane production (*i.e.* January 1978 to December 1983 for bare fallow conditions and January 1986 to December 1995 for sugarcane production).

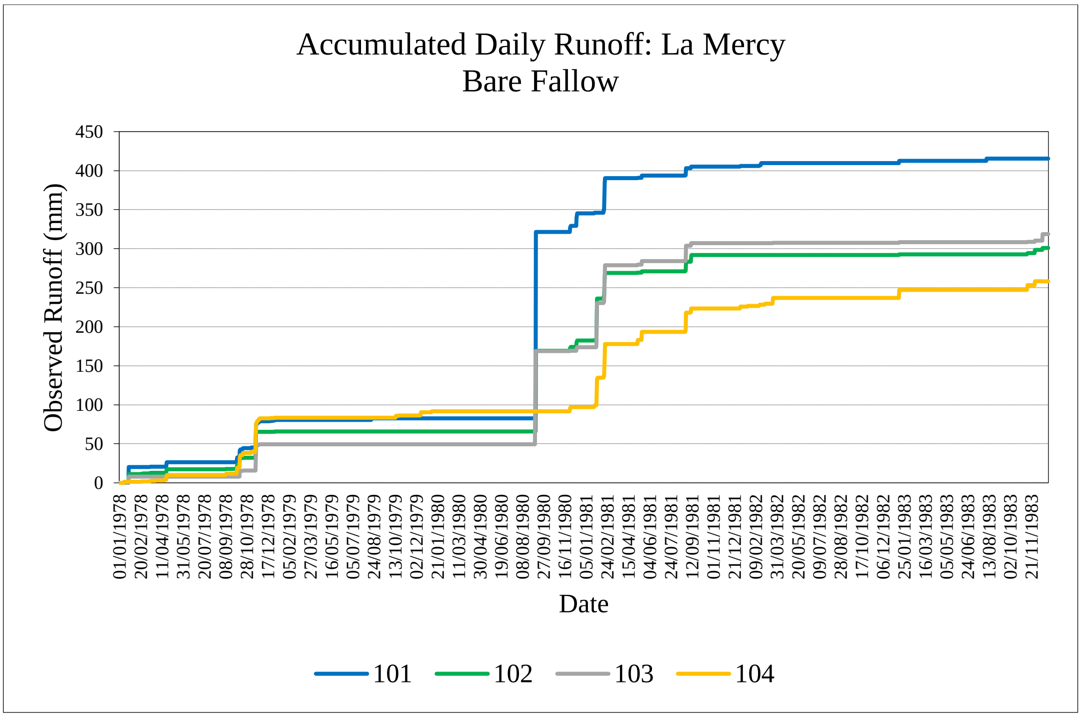


Figure 3.8 Accumulated daily runoff: La Mercy catchments, bare fallow (January 1978 to December 1983)

Under bare fallow conditions, Catchment 101 generally registered the highest runoff followed by Catchments 103, 102 and 104, as shown in Figure 3.8. Catchment 101 has the shortest overland flow distance (*i.e.* catchment length) followed by Catchments 103, 102 and 104 as shown in Table 3.1. Hence, runoff generated at the La Mercy catchments is inversely proportional to the length of overland flow, and this observation is in agreement with Stomph *et al.* (2002) who noted that shorter overland flow paths generate more runoff than longer overland flow paths. Furthermore, 100 % of soils in Catchments 101, 103 and 102 have moderately high to high runoff potentials while in Catchment 104, 90 % of the soils have moderately high to high runoff potentials and 10 % classified as moderately low, as shown in Table 3.2. Hence, the impact of the runoff potential of the soils on runoff generation is also evident. Classification of the runoff potential of a soil is governed by soil texture and infiltration rates. Hence, the higher the infiltration rate, the lower the runoff potential of the soil and vice versa. All the four catchments have clay and sandy clay soils which have moderately high to high runoff potentials and hence classified as having fair to poor infiltration potentials. However, Catchment 104 further has sandy loam soils which are classified as moderately low runoff potential soils having excessive to good infiltration potentials as shown in Table 3.2. However, the effect of catchment steepness on runoff was only noticeable in Catchment 101, although, according to Platford and Thomas (1985), catchment steepness impacts on the initiation of runoff. Catchment 101 is the steepest followed by Catchments 102, 104 and 103 as shown in Table 3.1. Hence, it appears the effects of overland flow distance and soils' runoff potentials masked the effects of catchment steepness on runoff generation.

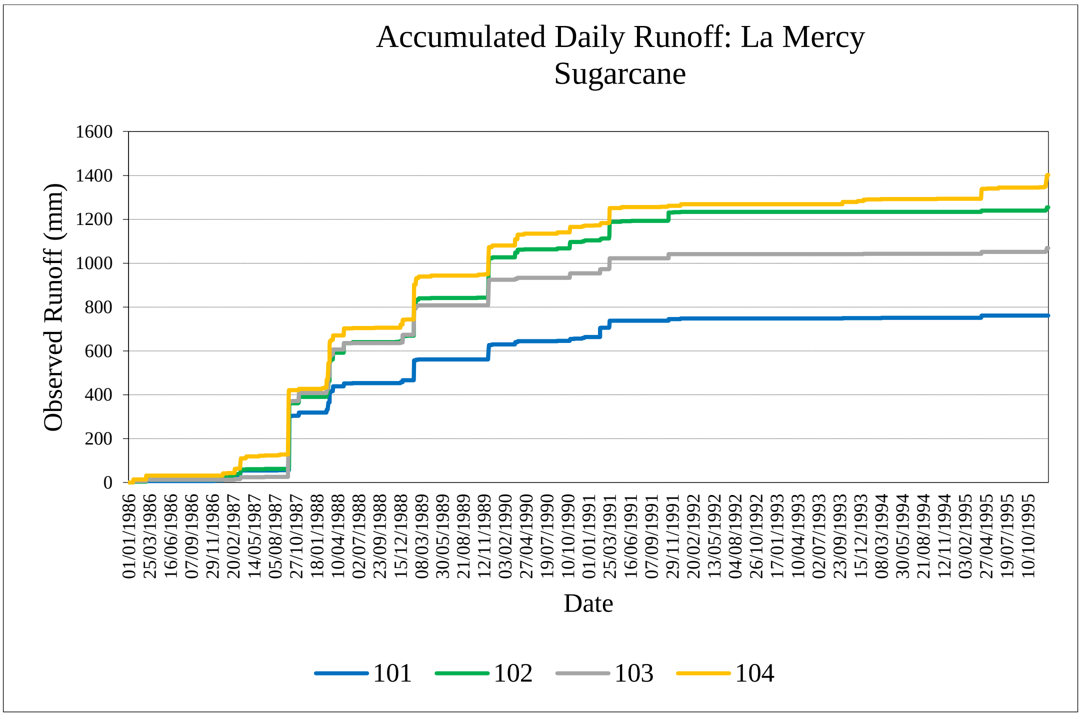


Figure 3.9 Accumulated daily runoff: La Mercy catchments, sugarcane production (January 1986 to December 1995)

During periods for which the four catchments were under sugarcane land cover, Catchment 101 which was under minimum tillage practice, recorded the lowest runoff followed by Catchments 103, 102 and 104 all of which were conventionally tilled, as shown in Figure 3.9. The relationship exhibited by Catchment 101, which registered the lowest runoff conforms to studies conducted by Haywood and Mitchell (1987) who showed that minimum tillage practices greatly reduce runoff compared to conventional tillage practices. In addition, Catchment 101 was under strip planting and harvesting implying that sugarcane cover was always present on some of the panels while the harvested panels either had mulch or burnt tops, hence reducing runoff generated further.

Catchment 104 which only had three strips under sugarcane land cover and the remaining two strips under permanent bare fallow conditions, generally recorded the highest runoff. These observations are consistent with Maher (1990) who stressed the need for maintenance of crop cover through strip planting so as to minimise generation of runoff.

The runoff from Catchment 103 was generally lower than runoff from Catchments 102 and 104 and all three catchments were conventionally tilled. Catchment 103 had no water conservation structures but had a natural depression which was sown with *Eragrostis curvula* before planting while Catchments 102 and 104 had water carrying terraces and grassed waterways. Thus, it is suspected that the natural depression in Catchment 103 allowed for impoundment of runoff and increased infiltration thereby reducing the runoff generated from Catchment 103.The impoundment of runoff increases the flow time and hence allowing additional time for infiltration in the process. In addition, it is postulated that the construction of water carrying terraces with the use of heavy machinery led to the formation of hard surfaces which inhibited infiltration and increased runoff generation in Catchments 102 and 104.

Similar to bare fallow conditions, the influence of catchment slope on runoff is not evident and this could be attributed to the crop cover and other management practices masking the impact of steepness on runoff. In addition, the effect of water conservation structures was generally not evident and this is because crop cover reduces runoff to a greater extent than soil and water conservation structures which concurs with conclusions drawn by Maher (1990).

A summary of the effects of catchment slope, overland flow path, soil type, tillage practice and conservation structures on runoff at the La Mercy catchments under sugarcane production is presented in Table 3.3.

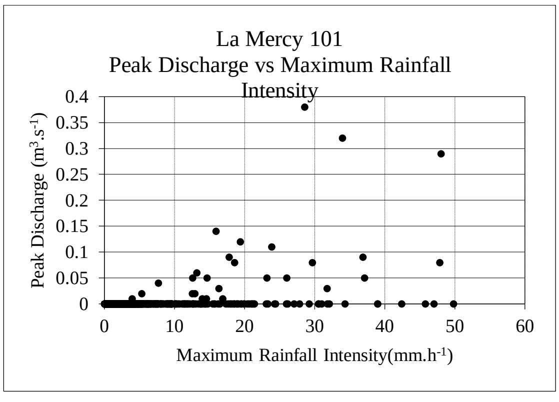
Table 3.3 Effects of catchment slope, overland flow path, soil type, tillage practice and conservation structures on runoff at the La Mercy catchments under sugarcane land cover

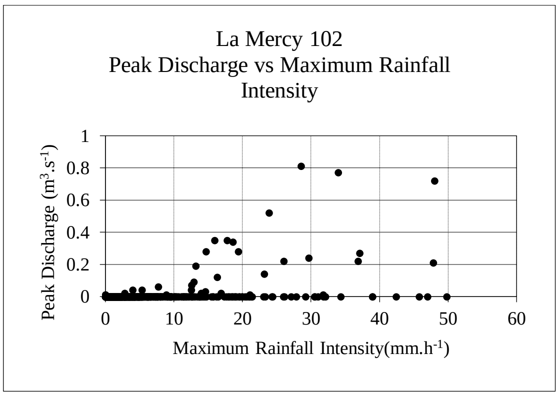
Feature	Discussion
Catchment slope	The influence of catchment slope on runoff is not evident and this could be attributed to the crop cover and other management practices masking the impact of steepness on runoff.
Overland flow path	Runoff increases with increase in distance of the overland flow path, hence, it appears the effects of tillage, crop cover and other management practices supersede the effects overland flow path on the generation of runoff.
Soil type	The impact of soils' runoff potentials on runoff generation is not evident. It is postulated that crop cover masks the impact of soil type on the generation of runoff.

Feature	Discussion
Tillage practice	Catchment 101 which was under minimum tillage practice, recorded the lowest runoff followed by Catchments 103, 102 and 104 all of which were conventionally tilled. Thus, the effect of tillage on runoff generated is evident.
Conservation structures	The effect of water conservation structures was generally not evident and this is because crop cover reduces runoff to a greater extent than soil and water conservation structures.

3.5.4 Daily peak discharge

Scatter plots of daily peak discharge against daily peak rainfall intensity and daily runoff are shown in Figure 3.10 and Figure 3.11 respectively for the four catchments under sugarcane cover conditions. It is evident that peak discharge increases with increases in peak rainfall intensity and runoff depth which is consistent with observations made by Schmidt and Schulze (1984) and Schulze (2011). From Figure 3.10 and Figure 3.11, it is also evident that a large number of daily peak rainfall intensities and runoff depths with no peak discharge were recorded at the La Mercy catchments. The inconsistencies between peak discharge and maximum rainfall intensity and runoff could be attributed to loss of some records as documented by Platford and Thomas (1985), Maher (1990) and Haywood (1991). Therefore, the peak discharge values for which either rainfall or runoff depth were missing were excluded from further analysis. The inconsistent peak discharge records for which either rainfall depth or runoff volume was missing are shown in Appendix 3.2.





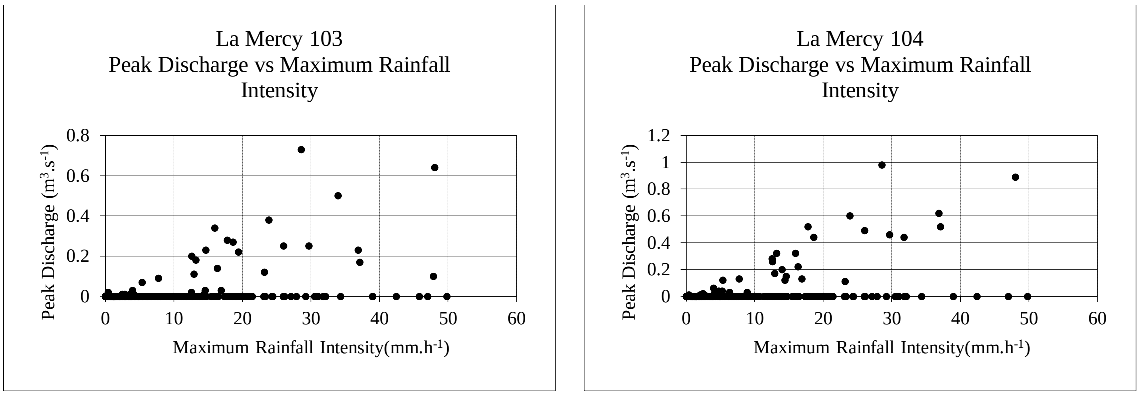


Figure 3.10 Daily peak discharge vs daily peak rainfall intensity: La Mercy catchments, Sugarcane cover, inconsistent events included (January 1986 to December 1995)

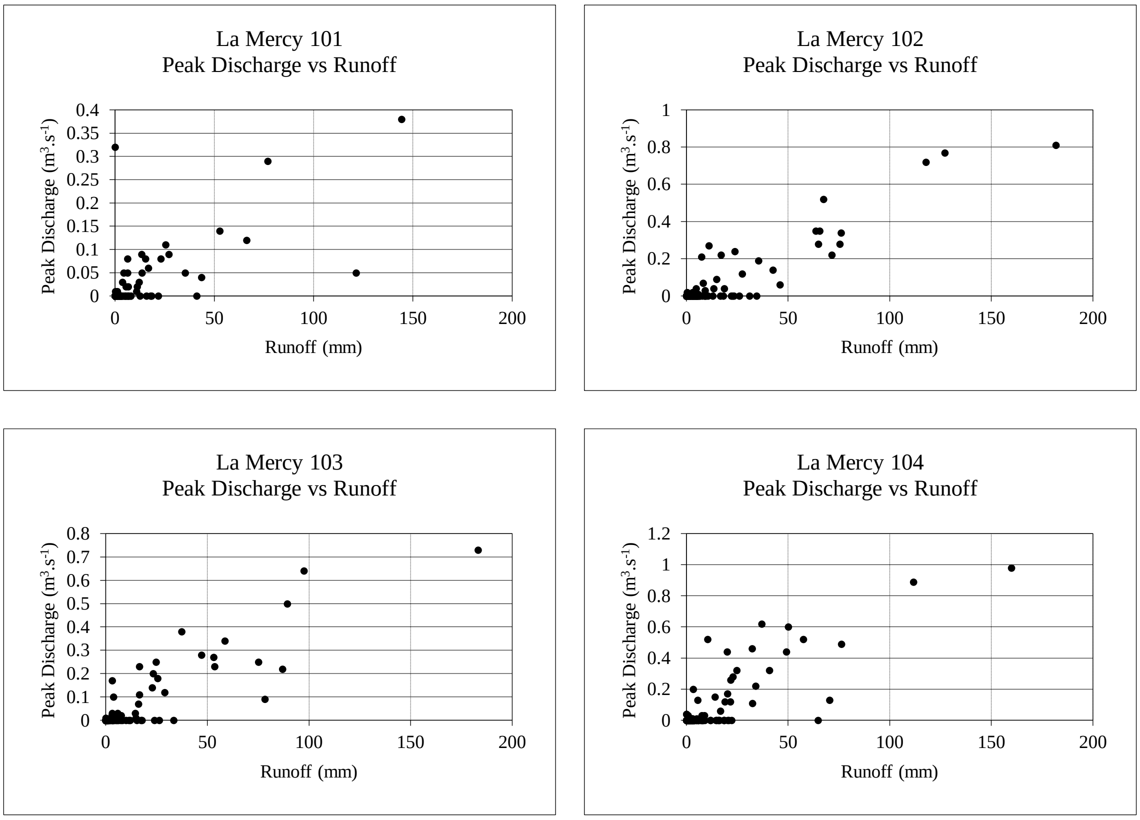


Figure 3.11 Daily peak discharge vs daily runoff: La Mercy catchments, Sugarcane cover, inconsistent events included (January 1986 to December 1995)

3.5.4.1 Relationships between event peak discharge and event runoff

Before analysing relationships between event peak discharge and event runoff for the La Mercy catchments under sugarcane land cover for the period January 1986 to December 1995, the inconsistent records discussed in Section 3.5.4 were eliminated and only consistent events used in the analysis. The inconsistent events included peak discharge values for which either rainfall or runoff depth were missing. Plots showing relationships between event peak discharge and event runoff for the La Mercy catchments under sugarcane land cover for the period January 1986 to December 1995 are shown in Figure 3.12 while the analysis and discussion of results follows thereafter.

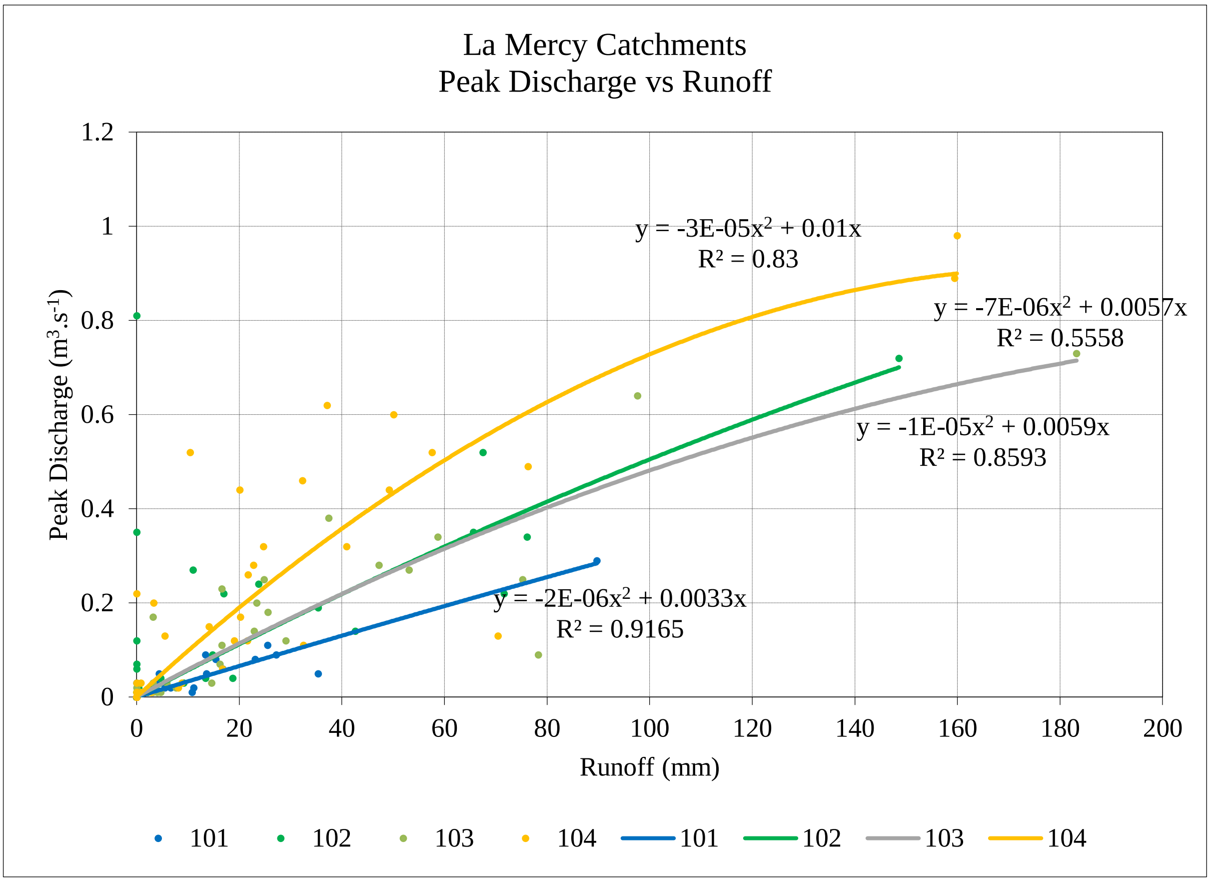


Figure 3.12 Relationships between peak discharge and runoff events: La Mercy catchments, Sugarcane cover, inconsistent events excluded (January 1986 to December 1995)

Catchment 101 recorded the lowest peak discharge per unit runoff depth followed by Catchments 103, 102 and 104, as shown in Figure 3.12. Furthermore, it is clear that peak discharge increases with runoff volume and area of catchment with Catchment 101 the smallest in area and generating the least runoff volume followed by Catchments 103, 102 and 104 the greatest in area, recorded the highest runoff volume. This relationship is in agreement with Schulze (2011) and Schmidt and Schulze (1984) who concluded that peak discharge increases with increases in runoff volume and increases in catchment area. Similar to volume of runoff, the effect of catchment slope on peak discharge is not evident and this could be attributed to the crop cover and other management practices masking the impact of steepness on peak discharge.

3.5.5 Event sediment yield

Scatter plots of event sediment yield for Catchments 101, 102 and 103 for the period 1984 – 1995 and Catchment 104 for the period 1986 – 1995 against event rainfall are shown in Figure 3.13 whereas scatter plots of event sediment yield against event runoff are shown in Figure 3.14. From Figure 3.14, it is evident that various inconsistencies of low sediment yield events with high runoff and vice versa were observed and this could be attributed to loss of records as documented by Maher (1990). The sediment yield records for which no runoff volume was available are shown in Appendix 3.3 while the large and suspicious events are highlighted with circles in Figure 3.14. A discussion of the large and suspicious sediment yield events hereby follows.

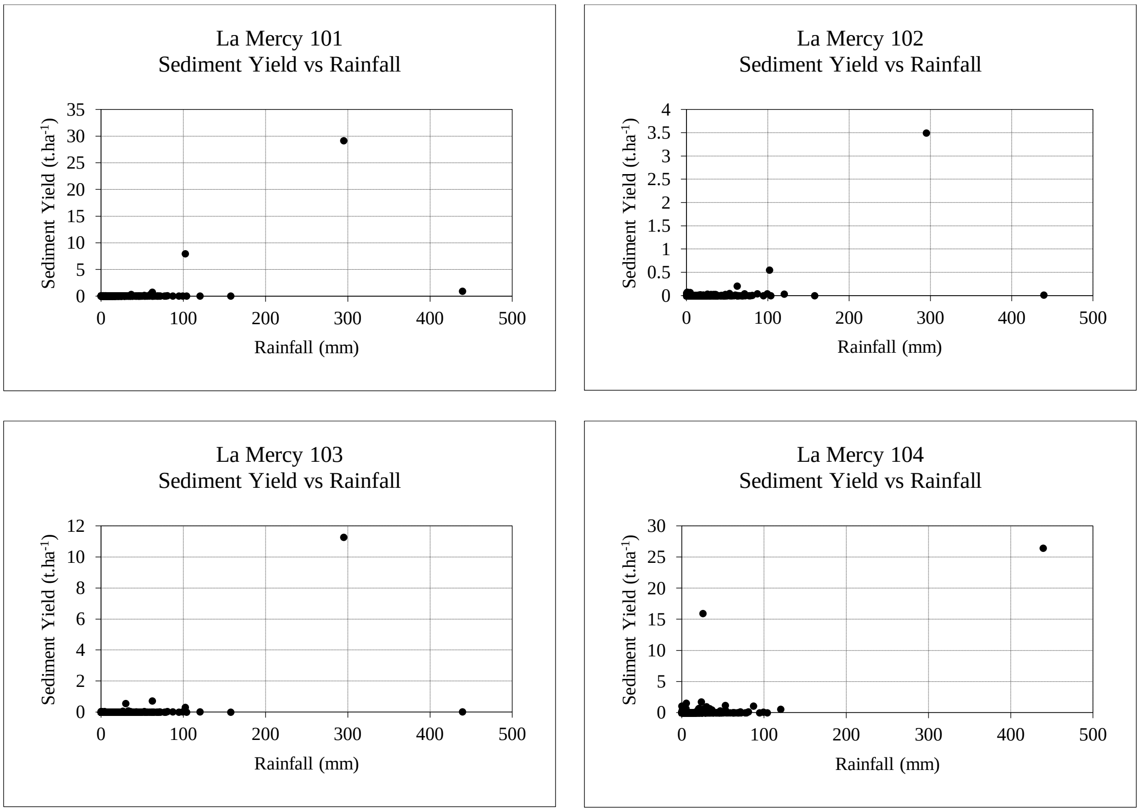


Figure 3.13 Event sediment yield vs event rainfall: La Mercy catchments, Sugarcane cover

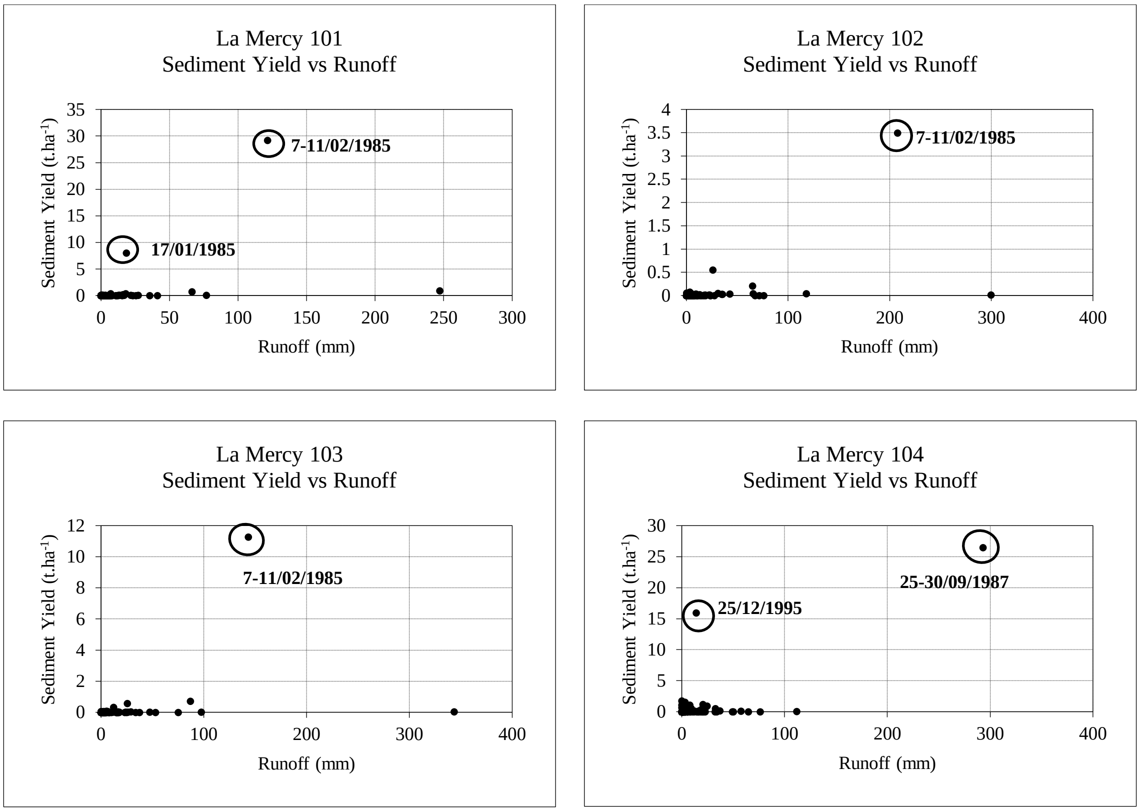


Figure 3.14 Sediment yield vs event runoff: La Mercy catchments, Sugarcane cover, high sediment yield events circled

From Figure 3.13 and Figure 3.14, it is clear that sediment yield from Catchment 101 is generally low for the period 1984 – 1995. However, two large sediment yield events for the period 17/01/1985 and 7-11/02/1985 with respective magnitudes of 8.0 $t.ha^{-1}$ and 29.2 $t.ha^{-1}$ are evident. Land management records show that Catchment 101 was planted with sugarcane in September 1984 implying that full canopy had developed by February 1985. Rainfall records show that it rained for 14 h on 17/01/1985 registering a rainfall depth of 102.2 mm, with an average rainfall intensity of 6.2 $mm.h^{-1}$ and peak discharge of 0 $m^3.s^{-1}$. Rainfall records for the period 7-11/02/1985 indicate that rainfall was received for 74 h with a total depth of 294.9 mm, an average intensity of 4.0 $mm.h^{-1}$, and maximum peak discharge of 0.32 $m^3.s^{-1}$. Based on the high rainfall and runoff records for the 17/01/1985 and 7-11/02/1985 events, high sediment yield events would be expected. However, extremely high sediment yield events for the period 17/01/1985 and 7-11/02/1985 coupled with no and very low peak discharge values respectively are not plausible. Furthermore, full canopy had been developed by the time they occurred implying that sediment yield should have been very low. Therefore, it is suspected that the extremely high sediment yield events could be attributed to sediment accumulation from construction of the waterway and spill over roads. Another explanation could be that sediment was transported and deposited in the waterway and along contours by smaller rainfall events, and later flushed out during periods of high runoff initiated by large storm events.

Similar to Catchment 101, the large sediment yield event in Catchment 102 occurred for the period of 7-11/02/1985 and events as discussed above. However, the sediment yield event in Catchment 102 is much smaller in magnitude with 3.5 $t.ha^{-1}$ registered on 7-11/02/1985. Land management records show that sugarcane was planted in September 1984 using conventional tillage implying that full canopy had been attained by February 1985, and Catchment 102 had water carrying terraces. Similar to Catchment 101, high sediment yield would be expected although the extremely high sediment yield event for the period 7-11/02/1985 is not plausible because full canopy had been developed by the time it occurred. Therefore, the extremely high sediment yield response could be attributed to sediment accumulated from the construction of water carrying terraces and the waterway. In addition, it could be that sediment was transported and deposited in the waterway and along contours by smaller rainfall events, and later flushed out during periods of high runoff initiated by large storm events. On the other hand, the seemingly lower sediment yield values compared to Catchment 101, could be attributed to the presence of water carrying terraces which capture sediment yield and runoff as opposed to spill over roads which spread runoff and sediment yield onto the field.

The large sediment yield measured from Catchment 103 and circled in Figure 3.14 confirms that similar relationships between sediment yield exist between Catchments 101, 102 and 103. The measured sediment of 11.3 $t.ha^{-1}$ arose from the same rainfall event of 7-11/02/1985 which also caused high sediment yield from Catchments 101 and 102. Records of land management show that Catchment 103 was planted with sugarcane in September 1984 using conventional tillage and Catchment 103 did not have any conservation structures although it had a natural depression sown with *Eragrostis curvula* before planting. Similar to Catchments 101 and 102, high sediment yield would be expected although the extremely high sediment yield event for the period 7-11/02/1985 is not plausible because full canopy had been developed by the time it occurred. Based on the above observation, the extremely high sediment yield event recorded on 7-11/02/1985 is not plausible and it is suspected that the natural depression sown with *Eragrostis curvula* contributed to the accumulation of sediment yield. Additionally, it is suspected that sediment was transported and deposited in the natural depression sown with *Eragrostis curvula* by smaller rainfall events, and later flushed out during periods of high runoff initiated by large storm events.

For Catchment 104, two large sediment yield events were recorded for the 25-30/09/1987 and 25/12/1995 with respective sediment yield values of 26.5 $t.ha^{-1}$ and 16.0 $t.ha^{-1}$. Generally, Catchment 104 had the highest sediment yield events. Records of land management indicate that Catchment 104 was under bare fallow up to December 1985 and sugarcane was planted on three strips only, using conventional tillage practice in January 1986. Land management records further show that sugarcane was harvested from the three panels in May 1987 and June 1995 implying that the three panels did not have sugarcane cover at the time of the above events. Therefore, the high sediment yield values could be attributed to the permanent bare fallow strips which were regularly harrowed, the low sugarcane cover on the three strips and the conventional tillage practice at planting. It is also suspected that repairs on the waterway and water carrying terraces could have given rise to the high sediment yield.

3.5.6 Relationships between accumulated sediment yield

To enable comparisons of relationships between sediment yield under sugarcane production, accumulated sediment yield plots were restricted to the periods under which all the four catchments were under sugarcane production (*i.e.* January 1986 to December 1995). The plot of accumulated sediment yield for the La Mercy catchments for the period 1986 – 1995 is shown in Figure 3.15. From Figure 3.15, it is evident that Catchment 104 consistently registered the highest sediment yield, followed by Catchments 101, 103 and 102 with sediment yield values of 60.8 $t.ha^{-1}$, 2.9 $t.ha^{-1}$, 1.4 $t.ha^{-1}$ and 1.0 $t.ha^{-1}$ respectively. The highly erodible soils, the two permanent bare fallow strips and the conventional tillage practice in Catchment 104 were responsible for the highest sediment yield registered in Catchment 104. It is postulated that the two permanent bare fallow strips which were frequently harrowed and the conventional tillage practice in Catchment 104 exposed the highly erodible soils to erosion, and resulted in the high sediment yield generated in Catchment 104 which is in agreement with MacVicar *et al.* (1977), Maher (1990) and USDA-ARS (2008). Estimates of the Modified Universal Soil Loss Equation area weighted soil erodibilities and cover factors for each of the La Mercy catchments supports this observation (*i.e.* high K and C factors lead to high erosion), as shown in Table 3.4.

Table 3.4 Soil erodibility and crop cover factors for each of the La Mercy Catchments

Catchment	Soil Erodibility, *K* factor	Cover factor, *C*	Sediment Yield ($t.ha^{-1}$)
101	0.26	0.31	2.9
102	0.17	0.31	1.0
103	0.17	0.31	1.4
104	0.39	0.71	60.8

On the other hand, Catchment 101 which was the steepest, under minimum tillage and strip planting/ harvesting and having spill over roads, registered the second highest sediment yield. The sediment yield response registered in Catchment 101 was attributed to the highly erodible soils and the steep slope.

Catchment 103 which was the flattest, registered the second lowest sediment yield and this is attributed to the conventional tillage practice and the lack of conservation structures.

Finally, the lowest sediment yield response in Catchment 102 is attributed to the low erodibility and the terraces which trap sediment yield. On the basis of erosion hazard rating, the sediment yield responses exhibited by the four catchments are plausible and in agreement with MacVicar *et al.* (1977). In general, the effects of low soil erodibility and cover and management practices were more pronounced in the reduction of sediment yield than the effect of conservation structures which is in agreement with observations made by Maher (2000). In addition, effects of catchment steepness on sediment yield were not evident and this was because soil erodibility and cover and management practices neutralised the effects of catchment steepness on sediment yield production as established by Le Roux *et al.* (2007). Similarly, the effects of tillage on sediment yield were not evident and it is postulated that that soil erodibility and cover and management practices masked the effects of tillage on sediment yield production.

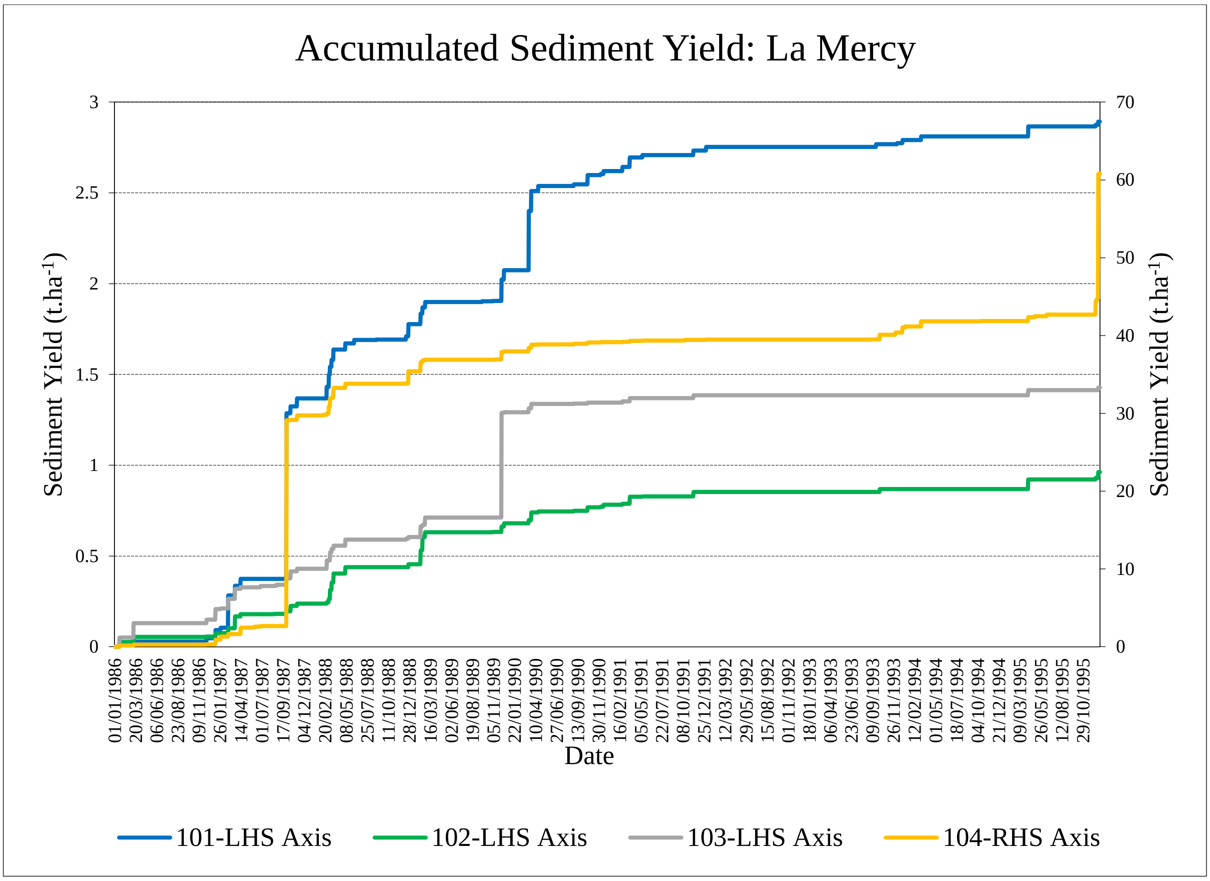


Figure 3.15 Accumulated sediment yield: La Mercy catchments, sugarcane cover

3.6 Conclusions

The rainfall recorded from the La Mercy catchments is consistent with rainfall recorded from the nearby La Mercy Airport and Tongaat stations and may be used with confidence.

Comparison of the observed daily rainfall and runoff data from the four La Mercy catchments showed some inconsistencies in the records (*i.e*. records where runoff volumes equal to zero but with rainfall greater than or equal to 25 mm, rainfall depth equal to zero but runoff volume greater than zero and runoff depth exceeding rainfall for some days), thereby resulting in an inconsistent relationship between rainfall and runoff. The inconsistencies between runoff and rainfall were attributed to loss of some records as documented by Platford and Thomas (1985), Maher (1990) and Haywood (1991) or a phasing problem where by daily rainfall and runoff were recorded on different days even though the duration of the event was < 24 h. However, correction for phasing problems and exclusion of the inconsistent events which were not affected by phasing gave rise to an improved and good association between rainfall and runoff, with R^2 coefficients of 0.980, 0.799, 0.794 and 0.767 for Catchments 101, 102, 103 and 104 respectively under bare fallow conditions while the respective R^2 coefficients under sugarcane cover conditions are 0.939, 0.880, 0.750 and 0.792.

Under bare fallow conditions, Catchment 101 generally registered the highest runoff events followed by Catchments 103, 102 and 104 and runoff was inversely proportional to the length of overland flow. In addition, the effects of soils' runoff potentials which are governed by soil texture and infiltration rates, on generation of runoff were evident although the effect of catchment slope was not evident. Therefore, it appears the effects of overland flow distance and soils' runoff potentials masked the effects of catchment steepness on runoff generation.

For periods when the four catchments were under sugarcane land cover, Catchment 101 which was under minimum tillage practice, exhibited the lowest runoff followed by Catchments 103, 102 and 104 all of which were under conventional tillage. Thus, this relationship is in agreement with Haywood and Mitchell (1987) who showed that minimum tillage practices greatly reduce runoff compared to conventional tillage practices. On the other hand, runoff increases with increases in the overland flow path and this contradicts observations made by Stomph *et al.* (2002) who noted that shorter overland flow paths generate more runoff than longer overland flow paths. It is postulated that the effects of tillage, crop cover and other management practices supersede the effects overland flow path on the generation of runoff. However, effects of catchment steepness, conservation structures and soils' runoff potentials on runoff generation were not evident and it could be attributed to the crop cover and other management practices masking their effects on runoff generation.

The peak discharge across the La Mercy catchments was observed to increase with increases in rainfall intensity, runoff volume and catchment area and the relationship is consistent with observations made by Schmidt and Schulze (1984) and Schulze (2011). The lowest peak discharge was recorded in Catchment 101 followed by Catchments 103, 102 and 104. Similar to volume of runoff, the effect of catchment slope on peak discharge were not evident and this could be attributed to the crop cover and other management practices masking the impact of steepness on peak discharge.

A scrutiny of the sediment yield values showed that Catchment 104 consistently registered the highest sediment yield, followed by Catchments 101, 103 and 102. Generally, low soil erodibility and cover and management practices had a greater effect on the reduction of sediment yield than conservation structures which is in agreement with observations made by Maher (2000). However, effects of catchment steepness and tillage practices on sediment yield were not evident and it could be attributed to the fact that soil erodibility and cover and management practices overrode the effects of catchment steepness on sediment yield production.

In conclusion, the various factors affecting catchment responses to runoff, peak discharge and sediment yield are summarised in Table 3.5 and they should be used to conceptualize parameters in models used for simulation and verification of hydrological and erosion processes on an event basis.

Table 3.5 Effects of catchment characteristics and management practices on runoff, peak discharge and sediment yield

Parameter	Runoff under bare fallow conditions	Runoff under sugarcane land cover	Peak discharge	Sediment yield
Catchment slope	0	0	0	0
Overland flow length	1	2		
Runoff potential of soils	1	0		
Minimum tillage practice	1	1		0
Conventional tillage practice	1	1		0
Conservation structures	0	0		
Cover and management practice	1	1		1
Catchment area			1	
Soil erosion hazard rating				1
Runoff			1	

Key:

0 Effect is not evident

1 Effect is evident and as expected

2 Effect is evident but not as expected

Effect not analysed

3.7 Acknowledgements

An appreciation is extended to the South African Sugarcane Research Institute (SASRI) for funding this research. In addition, Prof RE Schulze and Mr Geoff Maher are thanked for provision of information relating to the practices at the La Mercy catchments.

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3.9 Appendix 3.1: Inconsistent Rainfall and Runoff Data at the La Mercy Catchments

Inconsistent rainfall and runoff data at the La Mercy catchments are shown in Table 3.6.

Table 3.6 Inconsistent rainfall and runoff data at the La Mercy catchments

Catchment 101					Catchment 102					Catchment 103					Catchment 104				
Date	Rainfall (mm)	Maximum intensity (mm.h^{-1})	7 day antecedent rainfall (mm)	Observed Runoff (mm)	Date	Rainfall (mm)	Maximum intensity (mm.h^{-1})	7 day antecedent rainfall (mm)	Observed Runoff (mm)	Date	Rainfall (mm)	Maximum intensity (mm.h^{-1})	7 day antecedent rainfall (mm)	Observed Runoff (mm)	Date	Rainfall (mm)	Maximum intensity (mm.h^{-1})	7 day antecedent rainfall (mm)	Observed Runoff (mm)
12/01/1978	46.4	11.83	15.78	0.0	12/01/1978	46.4	11.83	15.78	0.0	12/01/1978	46.4	11.83	15.78	0.0	13/01/1978	0.0	0	62.2	0.7
21/02/1978	25.3	10.62	14.3	0.0	10/04/1978	27.4	16.88	0	0.0	21/02/1978	25.3	10.62	14.3	0.0	23/01/1978	53.6	14.31	38.15	0.0
27/03/1978	28.4	17.83	0	0.0	08/09/1978	34.4	8.31	0	0.0	27/03/1978	28.4	17.83	0	0.0	10/04/1978	27.4	16.88	0	0.0
10/04/1978	27.4	16.88	0	0.0	20/11/1978	0.0	14.21	36.22	1.7	10/04/1978	27.4	16.88	0	0.0	24/04/1978	0.0	0	47.55	0.1
08/09/1978	34.4	8.31	0	0.0	03/01/1979	0.0	0	41.5	0.2	22/04/1978	41.5	17.46	30.7	0.0	08/09/1978	34.4	8.31	0	0.0
09/09/1978	31.1	5.76	34.43	0.0	03/03/1979	35.6	7.03	1.7	0.0	08/09/1978	34.4	8.31	0	0.0	14/10/1978	0.0	0	68.6	0.2
20/10/1978	0.0	0	38.1	0.4	02/07/1979	38.1	12.81	3.65	0.0	09/09/1978	31.1	5.76	34.43	0.0	20/10/1978	0.0	0	38.1	0.6
20/11/1978	0.0	14.21	36.22	1.3	17/08/1979	28.9	4.22	2.65	0.0	03/03/1979	35.6	7.03	1.7	0.0	20/11/1978	0.0	14.21	36.22	1.0
03/01/1979	0.0	0	41.5	0.1	01/09/1979	57.6	19.55	0	0.0	02/07/1979	38.1	12.81	3.65	0.0	24/11/1978	0.0	0	132.7	0.9
03/03/1979	35.6	7.03	1.7	0.0	14/10/1979	28.0	6.38	10.8	0.0	17/08/1979	28.9	4.22	2.65	0.0	03/03/1979	35.6	7.03	1.7	0.0
02/07/1979	38.1	12.81	3.65	0.0	15/10/1979	40.1	14.95	38.79	0.0	01/09/1979	57.6	19.55	0	0.0	02/07/1979	38.1	12.81	3.65	0.0
17/08/1979	28.9	4.22	2.65	0.0	25/12/1979	26.1	10.08	0	0.0	14/10/1979	28.0	6.38	10.8	0.0	17/08/1979	28.9	4.22	2.65	0.0
01/09/1979	57.6	19.55	0	0.0	18/10/1980	31.5	5.32	5.35	0.0	15/10/1979	40.1	14.95	38.79	0.0	01/09/1979	57.6	19.55	0	0.0
14/10/1979	28.0	6.38	10.8	0.0	27/11/1980	26.1	8.35	25.1	0.0	25/12/1979	26.1	10.08	0	0.0	14/10/1979	28.0	6.38	10.8	0.0
15/10/1979	40.1	14.95	38.79	0.0	18/01/1981	25.6	0	0	0.0	18/10/1980	31.5	5.32	5.35	0.0	23/10/1979	0.0	0	23.86	0.1
25/12/1979	26.1	10.08	0	0.0	20/01/1981	25.6	0	0	0.0	27/11/1980	26.1	8.35	25.1	0.0	14/12/1979	0.0	0	51.5	0.4
18/10/1980	31.5	5.32	5.35	0.0	04/12/1981	28.3	13.27	15.2	0.0	18/01/1981	25.6	0	0	0.0	25/12/1979	26.1	10.08	0	0.0
27/11/1980	26.1	8.35	25.1	0.0	18/02/1982	45.9	20.93	24.58	0.0	20/01/1981	25.6	0	0	0.0	18/10/1980	31.5	5.32	5.35	0.0
01/12/1980	0.0	0	71.2	0.2	03/03/1982	28.6	12.66	0	0.0	04/12/1981	28.3	13.27	15.2	0.0	14/12/1980	57.9	18	14.87	0.0
16/12/1980	0.0	0	68.1	2.1	22/03/1982	36.1	11.13	41.52	0.0	18/02/1982	45.9	20.93	24.58	0.0	18/01/1981	25.6	0	0	0.0
18/01/1981	25.6	0	0	0.0	12/10/1982	26.4	15.09	5.83	0.0	03/03/1982	28.6	12.66	0	0.0	20/01/1981	25.6	0	0	0.0
20/01/1981	25.6	0	0	0.0	27/10/1982	40.9	5.9	2.15	0.0	12/10/1982	26.4	15.09	5.83	0.0	30/01/1981	36.0	0	43.6	0.0
30/01/1981	36.0	0	43.6	0.0	06/12/1982	25.9	9.97	9	0.0	27/10/1982	40.9	5.9	2.15	0.0	01/02/1981	0.0	0	25.6	33.2
31/01/1981	66.9	0	42.2	0.0	30/12/1982	33.7	22.43	7.62	0.0	06/12/1982	25.9	9.97	9	0.0	14/03/1981	0.0	0	15.2	0.0
04/12/1981	28.3	13.27	15.2	0.0	13/01/1983	42.6	0	0	0.0	30/12/1982	33.7	22.43	7.62	0.0	04/12/1981	28.3	13.27	15.2	0.0
03/03/1982	28.6	12.66	0	0.0	22/05/1983	51.6	26.99	15.3	0.0	13/01/1983	42.6	0	0	0.0	23/03/1982	0.0	0	77.6	2.0
22/03/1982	36.1	11.13	41.52	0.0	24/07/1983	28.0	4.22	12.8	0.0	22/05/1983	51.6	26.99	15.3	0.0	12/10/1982	26.4	15.09	5.83	0.0
12/10/1982	26.4	15.09	5.83	0.0	13/11/1983	0.0	0	21.65	2.0	24/07/1983	28.0	4.22	12.8	0.0	27/10/1982	40.9	5.9	2.15	0.0
27/10/1982	40.9	5.9	2.15	0.0	27/11/1983	39.9	9.26	11.5	0.0	13/11/1983	0.0	0	21.65	1.2	06/12/1982	25.9	9.97	9	0.0
06/12/1982	25.9	9.97	9	0.0	17/12/1983	51.5	23.18	5.6	0.0	27/11/1983	39.9	9.26	11.5	0.0	30/12/1982	33.7	22.43	7.62	0.0
30/12/1982	33.7	22.43	7.62	0.0	19/12/1983	0.0	0	64.8	0.2	17/12/1983	51.5	23.18	5.6	0.0	15/01/1983	0.0	0	0	2.1
13/01/1983	42.6	0	0	0.0	26/12/1983	27.3	13.15	5.04	0.0	19/12/1983	0.0	0	64.8	0.5	22/05/1983	51.6	26.99	15.3	0.0
22/05/1983	51.6	26.99	15.3	0.0	08/01/1984	0.0	0	31.4	2.8	26/12/1983	27.3	13.15	5.04	0.0	24/07/1983	28.0	4.22	12.8	0.0
24/07/1983	28.0	4.22	12.8	0.0	15/01/1984	0.0	0	5.1	3.1	02/01/1984	31.4	31.4	29.56	0.0	13/11/1983	0.0	0	21.65	8.7
12/11/1983	52.5	0	22.4	0.0	02/02/1984	0.0	0	30.2	6.2	08/01/1984	0.0	0	31.4	2.7	14/11/1983	0.0	0	9.06	1.8
27/11/1983	39.9	9.26	11.5	0.0	09/04/1984	47.0	0	0	0.0	15/01/1984	0.0	0	5.1	1.1	27/11/1983	39.9	9.26	11.5	0.0
17/12/1983	51.5	23.18	5.6	0.0	10/04/1984	35.8	0	0	0.0	17/02/1984	25.3	0	0	0.0	01/12/1983	0.0	0	78.5	0.1
26/12/1983	27.3	13.15	5.04	0.0	30/08/1984	27.8	5.23	9.4	0.0	11/04/1984	0.0	0	0	1.2	26/12/1983	27.3	13.15	5.04	0.0
02/01/1984	31.4	31.4	29.56	0.0	17/01/1985	86.2	18.87	0	0.0	21/05/1984	49.5	22.15	0	0.0	03/01/1984	0.0	0	33.7	1.1
08/01/1984	0.0	0	31.4	0.8	11/02/1985	0.0	0	0	5.8	30/08/1984	27.8	5.23	9.4	0.0	08/01/1984	0.0	0	31.4	6.4
15/01/1984	0.0	0	5.1	0.1	23/02/1985	0.0	0	72.8	2.7	17/01/1985	86.2	18.87	0	0.0	15/01/1984	0.0	0	5.1	3.9
02/02/1984	0.0	0	30.2	4.6	29/05/1985	35.4	13.9	0	0.0	11/02/1985	0.0	0	0	0.8	11/04/1984	0.0	0	0	3.7
11/04/1984	0.0	0	0	0.1	29/10/1985	27.1	3.12	0	0.0	23/02/1985	0.0	0	72.8	0.6	18/04/1984	0.0	0	16.9	0.8
21/05/1984	49.5	22.15	0	0.0	18/01/1986	49.3	11.61	6.34	0.0	29/05/1985	35.4	13.9	0	0.0	30/08/1984	27.8	5.23	9.4	0.0
24/07/1984	60.6	0	0	0.0	04/06/1986	25.4	6.04	0	0.0	29/10/1985	27.1	3.12	0	0.0	21/11/1984	0.0	0	39.4	0.8
30/08/1984	27.8	5.23	9.4	0.0	05/11/1986	38.4	13.39	12.32	0.0	02/11/1985	0.0	0	261.3	0.6	23/02/1985	0.0	0	72.8	0.2
17/01/1985	86.2	18.87	0	0.0	07/12/1986	45.5	20.37	9.44	0.0	18/01/1986	49.3	11.61	6.34	0.0	29/05/1985	35.4	13.9	0	0.0
23/02/1985	0.0	0	72.8	0.7	08/12/1986	43.0	12.82	54.94	0.0	04/06/1986	25.4	6.04	0	0.0	29/10/1985	27.1	3.12	0	0.0
29/05/1985	35.4	13.9	0	0.0	27/02/1987	0.0	0	94.8	0.2	05/11/1986	38.4	13.39	12.32	0.0	20/01/1986	0.0	0	91.3	0.1
18/01/1986	49.3	11.61	6.34	0.0	15/10/1987	0.0	0	26.3	1.7	07/12/1986	45.5	20.37	9.44	0.0	04/06/1986	25.4	6.04	0	0.0
11/03/1986	48.1	18.56	24.27	0.0	24/01/1988	28.3	13.86	1.8	0.0	08/12/1986	43.0	12.82	54.94	0.0	05/11/1986	38.4	13.39	12.32	0.0

Catchment 101				
Date	Rainfall (mm)	Maximum intensity (mm.h^{-1})	7 day antecedent rainfall (mm)	Observed Runoff (mm)
04/06/1986	25.4	6.04	0	0.0
05/11/1986	38.4	13.39	12.32	0.0
07/12/1986	45.5	20.37	9.44	0.0
30/01/1987	0.0	0	48	0.8
27/02/1987	0.0	0	94.8	6.7
27/06/1987	0.0	0	35.7	0.2
14/10/1987	0.0	0	26.3	0.3
15/10/1987	0.0	0	26.3	2.6
24/01/1988	28.3	13.86	1.8	0.0
08/02/1988	40.7	6.17	21.35	0.0
09/02/1988	30.2	6.1	62.06	0.0
16/02/1988	28.6	20.59	30.24	0.0
11/03/1988	0.0	0	172.91	0.9
16/03/1988	0.0	0	153.12	1.0
17/03/1988	0.0	0	49.32	0.2
17/12/1988	0.0	0	79	0.1
07/01/1989	33.2	11.83	0.24	0.0
05/02/1989	29.5	12.67	105.48	0.0
08/02/1989	0.0	0	292.9	0.7
15/04/1989	46.4	9.1	0	0.0
16/04/1989	43.2	5.16	46.4	0.0
01/07/1989	38.4	14.16	0	0.0
23/09/1989	28.3	5.55	9.77	0.0
16/10/1989	37.8	11.4	11.26	0.0
26/11/1989	0.0	0	6.6	1.7
27/11/1989	0.0	0	6.6	0.3
20/01/1990	33.3	25.94	0	0.0
23/01/1991	48.0	15.7	7.22	0.0
15/02/1991	28.0	17.91	12.03	0.0
26/03/1991	0.0	0	155.7	0.7
12/05/1991	45.0	9.06	36.4	0.0
20/06/1991	25.5	26.12	2.3	0.0
12/11/1991	31.0	21.4	2.2	0.0
08/10/1992	44.2	6.07	1.9	0.0
09/01/1993	76.5	30.55	1.65	0.0
08/02/1993	28.0	5.02	17.64	0.0
15/03/1993	38.0	24.38	2.4	0.0
23/09/1993	28.0	12.67	15.6	0.0
30/09/1993	30.0	4.9	40.1	0.0
07/10/1993	36.8	3.85	101.63	0.0
23/11/1993	43.8	19.97	3.7	0.0
03/03/1994	41.2	18.28	10.97	0.0
20/08/1994	33.0	4.99	8	0.0
14/10/1994	41.0	27.06	18.8	0.0
24/12/1994	31.1	8.76	3.9	0.0
09/03/1995	28.0	5.74	1.9	0.0
23/03/1995	85.5	15.68	0	0.0
17/06/1995	63.0	0	0	0.0
13/10/1995	27.0	4.44	3.2	0.0
25/11/1995	32.5	8.98	46.7	0.0

Catchment 102				
Date	Rainfall (mm)	Maximum intensity (mm.h^{-1})	7 day antecedent rainfall (mm)	Observed Runoff (mm)
08/02/1988	40.7	6.17	21.35	0.0
09/02/1988	30.2	6.1	62.06	0.0
16/02/1988	28.6	20.59	30.24	0.0
11/03/1988	0.0	0	172.91	0.9
16/03/1988	0.0	0	153.12	1.0
17/03/1988	0.0	0	49.32	0.3
23/03/1988	0.0	0	52.8	0.4
06/05/1988	0.0	0	120.17	1.4
17/12/1988	0.0	0	79	0.7
26/12/1988	0.0	0	72.09	0.4
05/02/1989	29.5	12.67	105.48	0.0
08/02/1989	0.0	0	292.9	0.7
23/09/1989	28.3	5.55	9.77	0.0
26/11/1989	0.0	0	6.6	5.3
27/11/1989	0.0	0	6.6	2.1
02/12/1989	0.0	0	201.3	0.6
20/01/1990	33.3	25.94	0	0.0
21/04/1990	0.0	0	12.7	0.1
23/01/1991	48.0	15.7	7.22	0.0
20/02/1991	0.0	0	133	0.1
26/03/1991	0.0	0	155.7	1.7
08/10/1992	44.2	6.07	1.9	0.0
09/01/1993	76.5	30.55	1.65	0.0
08/02/1993	28.0	5.02	17.64	0.0
15/03/1993	38.0	24.38	2.4	0.0
23/09/1993	28.0	12.67	15.6	0.0
30/09/1993	30.0	4.9	40.1	0.0
07/10/1993	36.8	3.85	101.63	0.0
23/11/1993	43.8	19.97	3.7	0.0
04/12/1993	45.8	12.18	9.32	0.0
28/12/1993	37.2	30.99	14.2	0.0
03/03/1994	41.2	18.28	10.97	0.0
09/03/1994	33.5	29.17	79.6	0.0
20/08/1994	33.0	4.99	8	0.0
14/10/1994	41.0	27.06	18.8	0.0
24/12/1994	31.1	8.76	3.9	0.0
09/03/1995	28.0	5.74	1.9	0.0
23/03/1995	85.5	15.68	0	0.0
17/06/1995	63.0	0	0	0.0
13/10/1995	27.0	4.44	3.2	0.0
25/11/1995	32.5	8.98	46.7	0.0

Catchment 103				
Date	Rainfall (mm)	Maximum intensity (mm.h^{-1})	7 day antecedent rainfall (mm)	Observed Runoff (mm)
09/01/1987	29.3	9.43	10.87	0.0
10/01/1987	26.5	23.08	40.16	0.0
27/06/1987	0.0	0	35.7	0.2
26/08/1987	0.0	0	38.6	0.1
30/09/1987	0.0	0	0	0.6
14/10/1987	0.0	0	26.3	0.6
15/10/1987	0.0	0	26.3	5.9
24/01/1988	28.3	13.86	1.8	0.0
09/02/1988	30.2	6.1	62.06	0.0
16/02/1988	28.6	20.59	30.24	0.0
11/03/1988	0.0	0	172.91	0.4
16/03/1988	0.0	0	153.12	0.9
17/03/1988	0.0	0	49.32	0.4
06/05/1988	0.0	0	120.17	0.1
29/08/1988	0.0	0	26.5	0.1
07/01/1989	33.2	11.83	0.24	0.0
03/02/1989	87.1	8.85	4.58	0.0
05/02/1989	29.5	12.67	105.48	0.0
08/02/1989	0.0	0	292.9	0.1
15/04/1989	46.4	9.1	0	0.0
16/04/1989	43.2	5.16	46.4	0.0
01/07/1989	38.4	14.16	0	0.0
23/09/1989	28.3	5.55	9.77	0.0
16/10/1989	37.8	11.4	11.26	0.0
26/11/1989	0.0	0	6.6	1.5
20/01/1990	33.3	25.94	0	0.0
20/04/1990	33.0	0	12.7	0.0
30/08/1990	53.0	9.3	24.36	0.0
06/12/1990	33.4	3.78	32.59	0.0
23/01/1991	48.0	15.7	7.22	0.0
15/02/1991	28.0	17.91	12.03	0.0
26/03/1991	0.0	0	155.7	0.3
10/05/1991	34.0	30.5	0	0.0
12/05/1991	45.0	9.06	36.4	0.0
20/06/1991	25.5	26.12	2.3	0.0
12/11/1991	31.0	21.4	2.2	0.0
01/01/1992	61.8	49.8	3.2	0.0
08/10/1992	44.2	6.07	1.9	0.0
09/01/1993	76.5	30.55	1.65	0.0
08/02/1993	28.0	5.02	17.64	0.0
15/03/1993	38.0	24.38	2.4	0.0
23/09/1993	28.0	12.67	15.6	0.0
30/09/1993	30.0	4.9	40.1	0.0
06/10/1993	31.0	4.99	73.36	0.0
07/10/1993	36.8	3.85	101.63	0.0
23/11/1993	43.8	19.97	3.7	0.0
05/12/1993	0.0	0	56.1	0.1
03/03/1994	41.2	18.28	10.97	0.0
09/03/1994	33.5	29.17	79.6	0.0
20/08/1994	33.0	4.99	8	0.0
14/10/1994	41.0	27.06	18.8	0.0
24/12/1994	31.1	8.76	3.9	0.0
09/03/1995	28.0	5.74	1.9	0.0
23/03/1995	85.5	15.68	0	0.0
17/06/1995	63.0	0	0	0.0
13/10/1995	27.0	4.44	3.2	0.0
25/11/1995	32.5	8.98	46.7	0.0
16/12/1995	40.0	13.94	15.6	0.0

Catchment 104				
Date	Rainfall (mm)	Maximum intensity (mm.h^{-1})	7 day antecedent rainfall (mm)	Observed Runoff (mm)
07/12/1986	45.5	20.37	9.44	0.0
08/12/1986	43.0	12.82	54.94	0.0
30/01/1987	0.0	0	48	0.3
27/02/1987	0.0	0	94.8	3.0
12/04/1987	0.0	0	36.5	0.4
15/04/1987	0.0	0	57.4	1.8
27/06/1987	0.0	0	35.7	0.6
26/08/1987	0.0	0	38.6	0.2
30/09/1987	0.0	0	0	1.3
24/01/1988	28.3	13.86	1.8	0.0
10/02/1988	0.0	0	92.3	1.5
27/02/1988	0.0	0	102.6	0.9
07/03/1988	0.0	0	143.1	1.0
16/03/1988	0.0	0	153.12	0.9
17/03/1988	0.0	0	49.32	0.3
06/05/1988	0.0	0	120.17	2.0
17/12/1988	0.0	0	79	1.4
18/12/1988	0.0	0	79	0.3
26/12/1988	0.0	0	72.09	0.2
08/02/1989	0.0	0	292.9	0.7
17/02/1989	0.0	0	62.7	2.7
23/09/1989	28.3	5.55	9.77	0.0
04/11/1989	0.0	0	39.5	0.1
26/11/1989	0.0	0	6.6	7.0
27/11/1989	0.0	0	6.6	3.2
02/12/1989	0.0	0	201.3	0.3
20/01/1990	33.3	25.94	0	0.0
27/03/1990	0.0	0	74.4	0.4
21/04/1990	0.0	0	12.7	0.3
26/04/1990	0.0	0	0	0.1
27/04/1990	0.0	0	0	0.1
20/02/1991	0.0	0	133	0.1
26/03/1991	0.0	0	155.7	0.6
08/10/1992	44.2	6.07	1.9	0.0
09/01/1993	76.5	30.55	1.65	0.0
08/02/1993	28.0	5.02	17.64	0.0
15/03/1993	38.0	24.38	2.4	0.0
30/09/1993	30.0	4.9	40.1	0.0
07/10/1993	36.8	3.85	101.63	0.0
05/12/1993	0.0	0	56.1	0.1
03/03/1994	41.2	18.28	10.97	0.0
20/08/1994	33.0	4.99	8	0.0
14/10/1994	41.0	27.06	18.8	0.0
24/12/1994	31.1	8.76	3.9	0.0
09/03/1995	28.0	5.74	1.9	0.0
23/03/1995	85.5	15.68	0	0.0
05/05/1995	0.0	0	39.6	1.2
18/06/1995	0.0	0	0	1.4
13/10/1995	27.0	4.44	3.2	0.0
26/12/1995	0.0	0.38	116.1	3.0

Catchment 101					Catchment 102					Catchment 103					Catchment 104				
Date	Rainfall (mm)	Maximum intensity (mm.h-1)	7 day antecedent rainfall (mm)	Observed Runoff (mm)	Date	Rainfall (mm)	Maximum intensity (mm.h-1)	7 day antecedent rainfall (mm)	Observed Runoff (mm)	Date	Rainfall (mm)	Maximum intensity (mm.h-1)	7 day antecedent rainfall (mm)	Observed Runoff (mm)	Date	Rainfall (mm)	Maximum intensity (mm.h-1)	7 day antecedent rainfall (mm)	Observed Runoff (mm)
										26/12/1995	0.0	0.38	116.1	3.0					

3.10 Appendix 3.2: Inconsistent Peak Discharge Data at the La Mercy Catchments

Inconsistent peak discharge records under both bare fallow and sugarcane land cover conditions are summarised in Table 3.7.

Table 3.7 Inconsistent peak discharge data at the La Mercy catchments under bare fallow and sugarcane cover conditions

Catchment 101			Catchment 102			Catchment 103			Catchment 104		
Date	Observed Runoff (mm)	Observed Peak Discharge ($m^3.s^{-1}$)	Date	Observed Runoff (mm)	Observed Peak Discharge ($m^3.s^{-1}$)	Date	Observed Runoff (mm)	Observed Peak Discharge ($m^3.s^{-1}$)	Date	Observed Runoff (mm)	Observed Peak Discharge ($m^3.s^{-1}$)
24/10/1984	0.1	0.0	24/10/1984	5.7	0.0	24/10/1984	4.1	0.0	18/01/1986	1.4	0.0
25/10/1984	0.0	0.0	25/10/1984	3.4	0.0	25/10/1984	3.4	0.0	19/01/1986	11.9	0.0
20/11/1984	0.1	0.0	29/10/1984	1.1	0.0	29/10/1984	1.1	0.0	20/01/1986	0.1	0.0
18/01/1985	18.5	0.0	01/11/1984	0.6	0.0	30/10/1984	0.6	0.0	11/03/1986	2.8	0.0
09/02/1985	0.0	0.3	20/11/1984	0.0	0.0	20/11/1984	0.7	0.0	12/03/1986	15.7	0.0
22/02/1985	17.9	0.0	18/01/1985	26.0	0.0	18/01/1985	12.1	0.0	09/01/1987	0.3	0.0
23/02/1985	0.7	0.0	22/02/1985	22.1	0.0	07/02/1985	0.1	0.0	10/01/1987	9.0	0.0
01/11/1985	6.9	0.0	23/02/1985	2.7	0.0	11/02/1985	0.8	0.0	29/01/1987	2.6	0.0
02/11/1985	1.3	0.0	01/11/1985	3.1	0.0	22/02/1985	11.4	0.0	30/01/1987	0.3	0.0
19/01/1986	4.9	0.0	19/01/1986	3.5	0.0	23/02/1985	0.6	0.0	25/02/1987	0.1	0.0
12/03/1986	2.4	0.0	11/03/1986	0.8	0.0	02/11/1985	0.6	0.0	26/02/1987	18.4	0.0
08/12/1986	2.1	0.0	12/03/1986	8.9	0.0	19/01/1986	6.4	0.0	27/02/1987	3.0	0.0
09/01/1987	0.2	0.0	09/01/1987	0.8	0.0	11/03/1986	0.5	0.0	07/03/1987	0.8	0.0
10/01/1987	5.4	0.0	10/01/1987	12.9	0.0	12/03/1986	5.4	0.0	20/03/1987	18.5	0.0
29/01/1987	2.9	0.0	29/01/1987	1.5	0.0	29/01/1987	0.4	0.0	21/03/1987	14.6	0.0
30/01/1987	0.8	0.0	26/02/1987	9.7	0.0	26/02/1987	3.2	0.0	22/03/1987	11.8	0.0
26/02/1987	15.9	0.0	27/02/1987	0.2	0.0	20/03/1987	1.3	0.0	23/03/1987	2.5	0.0
27/02/1987	6.7	0.0	20/03/1987	5.1	0.0	21/03/1987	2.6	0.0	11/04/1987	1.4	0.0
07/03/1987	0.9	0.0	21/03/1987	6.7	0.0	22/03/1987	2.0	0.0	12/04/1987	0.4	0.0
20/03/1987	5.6	0.0	22/03/1987	6.5	0.0	23/03/1987	1.8	0.0	13/04/1987	7.6	0.0
21/03/1987	5.1	0.0	23/03/1987	3.3	0.0	13/04/1987	0.3	0.0	15/04/1987	1.8	0.0
22/03/1987	6.1	0.0	13/04/1987	1.2	0.0	03/06/1987	0.4	0.0	21/05/1987	0.1	0.0
23/03/1987	3.1	0.0	03/06/1987	0.2	0.0	26/06/1987	0.8	0.0	22/05/1987	0.1	0.0
13/04/1987	0.4	0.0	26/06/1987	0.4	0.0	27/06/1987	0.2	0.0	03/06/1987	1.8	0.0
26/06/1987	0.5	0.0	16/08/1987	0.1	0.0	16/08/1987	0.5	0.0	26/06/1987	1.9	0.0
27/06/1987	0.2	0.0	30/09/1987	0.6	0.0	25/08/1987	0.6	0.0	27/06/1987	0.6	0.0
16/08/1987	0.1	0.0	15/10/1987	1.7	0.0	26/08/1987	0.1	0.0	16/08/1987	1.4	0.0
25/08/1987	0.3	0.0	06/11/1987	0.5	0.0	30/09/1987	0.6	0.0	25/08/1987	2.4	0.0
30/09/1987	0.5	0.0	07/11/1987	4.6	0.0	12/10/1987	0.1	0.0	26/08/1987	0.2	0.0
12/10/1987	0.1	0.0	08/11/1987	22.7	0.0	13/10/1987	0.8	0.0	22/09/1987	0.4	0.0
13/10/1987	0.1	0.0	11/11/1987	0.1	0.0	14/10/1987	0.6	0.0	30/09/1987	1.3	0.0
14/10/1987	0.3	0.0	12/11/1987	0.3	0.0	15/10/1987	5.9	0.0	06/11/1987	1.0	0.0
15/10/1987	2.6	0.0	05/03/1988	1.2	0.0	06/11/1987	0.7	0.0	07/11/1987	5.1	0.0
06/11/1987	0.5	0.0	11/03/1988	0.9	0.0	07/11/1987	8.2	0.0	08/11/1987	0.6	0.0
07/11/1987	2.5	0.0	15/03/1988	7.7	0.0	08/11/1987	26.3	0.0	12/11/1987	0.4	0.0
08/11/1987	12.6	0.0	16/03/1988	1.0	0.0	09/11/1987	0.2	0.0	08/02/1988	0.4	0.0
05/03/1988	0.2	0.0	17/03/1988	0.3	0.0	11/11/1987	0.6	0.0	09/02/1988	1.5	0.0
06/03/1988	0.2	0.0	22/03/1988	31.0	0.0	12/11/1987	0.6	0.0	10/02/1988	1.5	0.0
11/03/1988	0.9	0.0	23/03/1988	0.4	0.0	27/11/1987	0.1	0.0	16/02/1988	1.3	0.0
15/03/1988	3.7	0.0	06/05/1988	1.4	0.0	08/02/1988	0.4	0.0	17/02/1988	1.8	0.0
16/03/1988	1.0	0.0	07/06/1988	0.5	0.0	05/03/1988	0.2	0.0	18/02/1988	0.2	0.0
17/03/1988	0.2	0.0	08/06/1988	4.7	0.0	11/03/1988	0.4	0.0	25/02/1988	0.1	0.0
22/03/1988	21.8	0.0	28/08/1988	0.5	0.0	15/03/1988	7.4	0.0	27/02/1988	0.9	0.0
07/06/1988	0.3	0.0	28/11/1988	0.2	0.0	16/03/1988	0.9	0.0	06/03/1988	0.6	0.0
08/06/1988	1.5	0.0	29/11/1988	0.1	0.0	17/03/1988	0.4	0.0	07/03/1988	1.0	0.0
16/12/1988	4.3	0.0	16/12/1988	5.5	0.0	22/03/1988	24.0	0.0	14/03/1988	0.1	0.0
17/12/1988	0.1	0.0	17/12/1988	0.7	0.0	06/05/1988	0.1	0.0	15/03/1988	5.9	0.0
24/12/1988	8.0	0.0	24/12/1988	16.8	0.0	08/06/1988	0.2	0.0	16/03/1988	0.9	0.0
25/12/1988	1.0	0.0	25/12/1988	4.9	0.0	28/08/1988	0.2	0.0	17/03/1988	0.3	0.0
03/02/1989	0.6	0.0	26/12/1988	0.4	0.0	29/08/1988	0.1	0.0	21/03/1988	0.1	0.0

Catchment 101			Catchment 102			Catchment 103			Catchment 104		
Date	Observed Runoff (mm)	Observed Peak Discharge ($m^3.s^{-1}$)	Date	Observed Runoff (mm)	Observed Peak Discharge ($m^3.s^{-1}$)	Date	Observed Runoff (mm)	Observed Peak Discharge ($m^3.s^{-1}$)	Date	Observed Runoff (mm)	Observed Peak Discharge ($m^3.s^{-1}$)
08/02/1989	0.7	0.0	07/01/1989	1.1	0.0	16/12/1988	2.3	0.0	22/03/1988	20.4	0.0
15/02/1989	2.8	0.0	04/02/1989	1.0	0.0	24/12/1988	33.5	0.0	06/05/1988	2.0	0.0
16/02/1989	0.5	0.0	08/02/1989	0.7	0.0	25/12/1988	1.0	0.0	07/06/1988	0.1	0.0
25/02/1989	1.3	0.0	10/02/1989	0.5	0.0	04/02/1989	0.1	0.0	08/06/1988	1.1	0.0
26/02/1989	0.2	0.0	15/02/1989	10.6	0.0	08/02/1989	0.1	0.0	28/08/1988	0.4	0.0
13/03/1989	0.4	0.0	16/02/1989	3.3	0.0	15/02/1989	10.0	0.0	04/09/1988	0.4	0.0
03/11/1989	0.0	0.0	23/02/1989	0.2	0.0	16/02/1989	1.4	0.0	28/11/1988	0.2	0.0
26/11/1989	1.7	0.0	25/02/1989	4.8	0.0	25/02/1989	3.2	0.0	29/11/1988	0.3	0.0
27/11/1989	0.3	0.0	26/02/1989	2.0	0.0	26/02/1989	0.3	0.0	16/12/1988	14.9	0.0
14/12/1989	3.2	0.0	13/03/1989	0.5	0.0	26/11/1989	1.5	0.0	17/12/1988	1.4	0.0
15/12/1989	0.1	0.0	15/04/1989	0.1	0.0	14/12/1989	0.5	0.0	18/12/1988	0.3	0.0
15/03/1990	2.9	0.0	16/04/1989	1.8	0.0	15/03/1990	0.4	0.0	24/12/1988	18.6	0.0
16/03/1990	7.0	0.0	01/07/1989	0.1	0.0	16/03/1990	3.8	0.0	25/12/1988	3.0	0.0
25/03/1990	3.0	0.0	16/10/1989	0.4	0.0	25/03/1990	3.6	0.0	26/12/1988	0.2	0.0
26/03/1990	0.7	0.0	03/11/1989	0.4	0.0	26/03/1990	0.8	0.0	07/01/1989	0.9	0.0
20/04/1990	0.3	0.0	26/11/1989	5.3	0.0	19/10/1990	15.3	0.0	05/02/1989	1.0	0.0
30/08/1990	1.0	0.0	27/11/1989	2.1	0.0	20/10/1990	5.0	0.0	08/02/1989	0.7	0.0
19/10/1990	6.4	0.0	02/12/1989	0.6	0.0	16/02/1991	17.4	0.0	14/02/1989	0.2	0.0
20/10/1990	3.2	0.0	14/12/1989	3.9	0.0	18/02/1991	0.8	0.0	15/02/1989	20.8	0.0
03/11/1990	0.2	0.0	15/12/1989	0.9	0.0	19/02/1991	0.3	0.0	16/02/1989	7.3	0.0
04/11/1990	0.1	0.0	15/03/1990	3.8	0.0	26/03/1991	0.3	0.0	17/02/1989	2.7	0.0
05/11/1990	0.3	0.0	16/03/1990	18.2	0.0	13/11/1991	0.1	0.0	25/02/1989	5.8	0.0
06/11/1990	0.5	0.0	25/03/1990	9.1	0.0	15/11/1991	17.8	0.0	26/02/1989	1.8	0.0
06/12/1990	1.0	0.0	26/03/1990	4.5	0.0	03/12/1993	0.1	0.0	13/03/1989	0.3	0.0
07/12/1990	2.3	0.0	20/04/1990	0.5	0.0	04/12/1993	0.7	0.0	15/04/1989	0.2	0.0
15/12/1990	2.5	0.0	21/04/1990	0.1	0.0	05/12/1993	0.1	0.0	16/04/1989	3.2	0.0
16/12/1990	0.4	0.0	30/08/1990	4.4	0.0	28/12/1993	0.5	0.0	17/04/1989	0.3	0.0
18/12/1990	0.4	0.0	19/10/1990	23.3	0.0	29/12/1993	0.3	0.0	01/07/1989	0.6	0.0
19/12/1990	0.6	0.0	20/10/1990	5.9	0.0	30/12/1993	0.6	0.0	24/09/1989	0.3	0.0
16/02/1991	41.1	0.0	03/11/1990	0.2	0.0	09/04/1995	0.4	0.0	16/10/1989	0.3	0.0
18/02/1991	0.9	0.0	05/11/1990	0.4	0.0	11/04/1995	0.4	0.0	17/10/1989	0.1	0.0
19/02/1991	0.6	0.0	06/11/1990	0.3	0.0				21/10/1989	3.0	0.0
26/02/1991	0.0	0.0	06/12/1990	0.5	0.0				03/11/1989	1.1	0.0
26/03/1991	0.7	0.0	07/12/1990	1.7	0.0				04/11/1989	0.1	0.0
10/05/1991	0.2	0.0	15/12/1990	2.9	0.0				11/11/1989	0.1	0.0
11/05/1991	0.2	0.0	18/12/1990	0.9	0.0				12/11/1989	0.8	0.0
13/11/1991	0.1	0.0	19/12/1990	0.8	0.0				16/11/1989	0.1	0.0
15/11/1991	7.9	0.0	24/01/1991	0.1	0.0				26/11/1989	7.0	0.0
01/01/1992	1.4	0.0	15/02/1991	0.1	0.0				27/11/1989	3.2	0.0
02/01/1992	0.9	0.0	16/02/1991	3.8	0.0				28/11/1989	0.2	0.0
06/10/1993	0.7	0.0	18/02/1991	2.7	0.0				02/12/1989	0.3	0.0
04/12/1993	0.3	0.0	19/02/1991	1.0	0.0				03/12/1989	0.1	0.0
10/12/1993	0.0	0.0	20/02/1991	0.1	0.0				07/12/1989	0.1	0.0
28/12/1993	1.0	0.0	25/02/1991	0.6	0.0				14/12/1989	4.9	0.0
09/03/1994	0.2	0.0	26/02/1991	0.3	0.0				15/12/1989	1.3	0.0
22/12/1995	0.1	0.0	10/05/1991	1.3	0.0				16/12/1989	0.1	0.0
			11/05/1991	1.5	0.0				15/03/1990	7.9	0.0
			12/05/1991	0.2	0.0				16/03/1990	22.3	0.0
			20/06/1991	0.7	0.0				25/03/1990	15.9	0.0
			30/10/1991	0.2	0.0				26/03/1990	3.9	0.0
			12/11/1991	0.7	0.0				27/03/1990	0.4	0.0
			13/11/1991	3.1	0.0				02/04/1990	0.4	0.0
			15/11/1991	34.6	0.0				16/04/1990	0.2	0.0
			30/11/1991	0.1	0.0				20/04/1990	3.7	0.0
			04/12/1991	0.3	0.0				21/04/1990	0.3	0.0
			05/12/1991	0.1	0.0				26/04/1990	0.1	0.0
			01/01/1992	0.8	0.0				27/04/1990	0.1	0.0

Catchment 101			Catchment 102			Catchment 103			Catchment 104		
Date	Observed Runoff (mm)	Observed Peak Discharge ($m^3.s^{-1}$)	Date	Observed Runoff (mm)	Observed Peak Discharge ($m^3.s^{-1}$)	Date	Observed Runoff (mm)	Observed Peak Discharge ($m^3.s^{-1}$)	Date	Observed Runoff (mm)	Observed Peak Discharge ($m^3.s^{-1}$)
			02/01/1992	1.7	0.0				30/08/1990	5.9	0.0
			06/10/1993	0.2	0.0				19/10/1990	16.2	0.0
			23/12/1995	1.4	0.0				20/10/1990	8.3	0.0
			24/12/1995	1.8	0.0				03/11/1990	0.1	0.0
									05/11/1990	0.3	0.0
									06/11/1990	0.2	0.0
									06/12/1990	0.8	0.0
									07/12/1990	2.4	0.0
									15/12/1990	2.2	0.0
									16/12/1990	0.2	0.0
									18/12/1990	0.4	0.0
									19/12/1990	0.3	0.0
									23/01/1991	0.1	0.0
									25/01/1991	0.3	0.0
									15/02/1991	0.2	0.0
									16/02/1991	3.4	0.0
									17/02/1991	0.2	0.0
									18/02/1991	4.0	0.0
									19/02/1991	2.1	0.0
									20/02/1991	0.1	0.0
									25/02/1991	0.5	0.0
									26/02/1991	0.5	0.0
									26/03/1991	0.6	0.0
									10/05/1991	0.2	0.0
									11/05/1991	3.8	0.0
									12/05/1991	0.3	0.0
									20/06/1991	0.6	0.0
									07/07/1991	0.1	0.0
									09/10/1991	0.1	0.0
									10/10/1991	0.2	0.0
									13/10/1991	0.1	0.0
									30/10/1991	0.7	0.0
									12/11/1991	1.2	0.0
									13/11/1991	3.1	0.0
									14/11/1991	0.5	0.0
									15/11/1991	64.8	0.0
									04/12/1991	0.1	0.0
									05/12/1991	0.1	0.0
									01/01/1992	1.5	0.0
									02/01/1992	4.1	0.0
									03/01/1992	0.8	0.0
									23/09/1993	1.0	0.0
									05/10/1993	1.1	0.0
									06/10/1993	8.1	0.0
									23/11/1993	1.0	0.0
									03/12/1993	0.1	0.0
									04/12/1993	3.6	0.0
									05/12/1993	0.1	0.0
									28/12/1993	6.0	0.0
									29/12/1993	0.5	0.0
									10/01/1994	0.5	0.0
									09/03/1994	2.4	0.0
									15/10/1994	0.1	0.0
									11/04/1995	3.1	0.0
									02/05/1995	0.4	0.0
									03/05/1995	0.8	0.0
									05/05/1995	1.2	0.0

Catchment 101			Catchment 102			Catchment 103			Catchment 104		
Date	Observed Runoff (mm)	Observed Peak Discharge ($m^3.s^{-1}$)	Date	Observed Runoff (mm)	Observed Peak Discharge ($m^3.s^{-1}$)	Date	Observed Runoff (mm)	Observed Peak Discharge ($m^3.s^{-1}$)	Date	Observed Runoff (mm)	Observed Peak Discharge ($m^3.s^{-1}$)
									17/06/1995	5.0	0.0
									18/06/1995	1.4	0.0
									25/11/1995	1.0	0.0
									17/12/1995	0.0	0.0
									18/12/1995	0.0	0.0

3.11 Appendix 3.3: Inconsistent Sediment Yield Events at the La Mercy Catchments under Sugarcane Cover Conditions

The inconsistent sediment yield records under sugarcane cover conditions at the La Mercy catchments are shown in Table 3.8.

Table 3.8 Inconsistent sediment yield data at the La Mercy catchments under sugarcane cover conditions

Catchment 101			Catchment 102			Catchment 103			Catchment 104		
Date	Observed Runoff (mm)	Observed Soil loss ($t.ha^{-1}$)	Date	Observed Runoff (mm)	Observed Soil loss ($t.ha^{-1}$)	Date	Observed Runoff (mm)	Observed Soil loss ($t.ha^{-1}$)	Date	Observed Runoff (mm)	Observed Soil loss ($t.ha^{-1}$)
11/02/1985	0.0	29.16	02/11/1985	0.0	0.006	08/12/1986	0.0	0.018	07/12/1986	0.0	0.017
16/10/1987	0.0	0.038	08/12/1986	0.0	0.003	10/01/1987	0.0	0.059	08/12/1986	0.0	0.021
28/08/1988	0.0	0.002	16/10/1987	0.0	0.03	16/10/1987	0.0	0.038	16/10/1987	0.0	0.028
24/09/1989	0.0	0.004	06/03/1988	0.0	0.017	17/12/1988	0.0	0.006	11/03/1988	0.0	1.093
23/09/1993	0.0	0.015	11/04/1995	0.0	0.054	03/02/1989	0.0	0.029	15/10/1991	0.0	0.076
30/12/1993	0.0	0.017	17/12/1995	0.0	0.009	15/12/1989	0.0	0.003	10/12/1993	0.0	0.007
11/04/1995	0.0	0.055				30/08/1990	0.0	0.002	30/12/1993	0.0	0.672
17/12/1995	0.0	0.009				26/02/1991	0.0	0.008	24/03/1995	0.0	0.003
									17/12/1995	0.0	1.752

4 VERIFICATION OF RUNOFF VOLUME, PEAK DISCHARGE AND SEDIMENT YIELD SIMULATED USING THE *ACRU* MODEL FOR BARE FALLOW AND SUGARCANE FIELDS

This chapter has been accepted for publication in *Water SA* subject to revision.

Otim, D, Smithers, J, Senzanje, A and van Antwerpen, R. "In press". Verification of runoff volume, peak discharge and sediment yield simulated using the ACRU model for bare fallow and sugarcane fields. *Water SA* "In press".

Abstract

The Agricultural Catchments Research Unit (*ACRU*) model is a daily time step physical-conceptual agrohydrological model with various applications, with design hydrology being one of them (Schulze *et al.*, 1995). Model verification is a measure of a model's performance and streamflow, soil water content and sediment yield simulated by the *ACRU* model have been extensively verified against observed data in southern Africa and internationally (Schulze *et al.*, 1995; Schulze, 2008; Schulze, 2011). The primary objective of this study was to verify simulated runoff volume, peak discharge and sediment yield against observed data from small catchments, under both bare fallow conditions and sugarcane production, which were located at La Mercy in South Africa and which is now the site of King Shaka International Airport. The study area comprised four research catchments, namely Catchments 101, 102, 103 and 104, and the catchments were monitored both under bare fallow conditions and sugarcane production with different management practices. The observed data comprised daily rainfall, maximum and minimum temperature, A-pan evaporation and runoff for the period 1978 – 1995, and peak discharge and sediment yield for the period 1984 – 1995. The data were checked for errors and inconsistencies, and inconsistent records were excluded from analysis. Runoff volume, peak discharge and sediment yield were simulated with the *ACRU* model and verified against the respective observed data. In general, the relative sequences and orders of magnitude of runoff volume from the La Mercy catchments were reasonably simulated under both bare fallow and sugarcane land cover conditions. In addition, the correlations between observed and simulated daily runoff volumes and peak discharge were acceptable (*i.e.* slopes of regression lines close to unity and $R^2 \geq 0.6$). Similarly, the correlation between observed and simulated sediment yield

was also good. From the results obtained, it is concluded that the *ACRU* model is suitable for the simulation of runoff volume, peak discharge and sediment yield from catchments under both bare fallow and sugarcane land cover in South Africa. Therefore, the *ACRU* model can be confidently applied in the development of updated design norms for soil and water conservation structures in the sugar industry in South Africa.

Keywords: *ACRU*, La Mercy, Peak Discharge, Sediment Yield, Streamflow, Sugarcane

4.1 Introduction

The Agricultural Catchments Research Unit (*ACRU*) model is a daily time step, physical-based conceptual agrohydrological model (Schulze, 1975; Schulze *et al.*, 1995; Smithers and Schulze, 1995; Smithers *et al.*, 1996). In addition, the *ACRU* model is not an optimising model and parameters are generally estimated from physical characteristics of catchments. It is a multi-purpose model with application in design hydrology, crop yield modelling, reservoir yield simulation, irrigation water demand and supply, and assessment of climate change, land use and management impacts (Schulze *et al.*, 1995; Jewitt and Schulze, 1999). The *ACRU* model, together with simulated outputs such as streamflow, soil water content and sediment yield, has been extensively verified against observed data in southern Africa and internationally (Schulze, 2008; Schulze, 2011). To verify is to determine the correctness of simulated output through comparison with observed data, hence model verification is a measure of the model's performance (Schulze, 2011). Model verification can be in terms of either absolute output values or in terms of the relative sequences and orders of magnitude of output responses (Lumsden *et al.*, 2003). For simulations using a daily time-step model to be acceptable, the absolute difference between the sum of simulated streamflow and the sum of observed streamflow should be less than 10%, the slope of the regression line of simulated vs observed values should be close to unity and the minimum acceptable coefficient of determination (R^2) should be 0.60 (Schulze and Smithers, 1995b). In addition, model performance is examined based on its ability to generate reasonable key statistics, percentiles and extreme values (Rashid *et al.*, 2015), and to maintain similarities in shapes and distributions of peaks between observed and simulated values (Kim *et al.*, 2014). Continuous assessment of the accuracy and sensitivity of models is vital in the prioritisation of model structure modifications and the identification of more efficient parameterisations (Merritt *et al.*, 2003).

The results reported in this paper are a component of a wider study whose aim was to develop updated design norms for soil and water conservation structures in the sugar industry in South Africa. The currently used nomograph for the design of soil and water conservation structures in the sugar industry in South Africa was developed by Platford (1987), who used long term annual soil loss simulated using the Universal Soil Loss Equation (USLE). However, erosion occurs on an event basis and Platford (1987) did not conduct any verification on the USLE prior to development of the nomograph. Therefore, the objective of this paper was to verify the runoff volume, peak discharge and sediment yield simulated by the *ACRU* model against observed data at the La Mercy catchments in South Africa, under both bare fallow and sugarcane land cover conditions and with various management practices.

4.2 Simulation of Stormflow Volume, Peak Discharge and sediment Yield in the *ACRU* Model

The *ACRU* model (Figure 4.1) is a deterministic agrohydrological model which is continuously being developed at the University of KwaZulu-Natal, South Africa. The *ACRU* model uses a modified SCS algorithm for the simulation of daily runoff and peak discharge, and the Modified Universal Soil Loss Equation (MUSLE) for the simulation of sediment yield (Lorentz *et al.*, 2012). The *ACRU* modelling system is summarised in Figure 4.1 while the subsequent sections contain brief overviews of the simulation of stormflow volume, peak discharge and sediment yield used in the *ACRU* model.

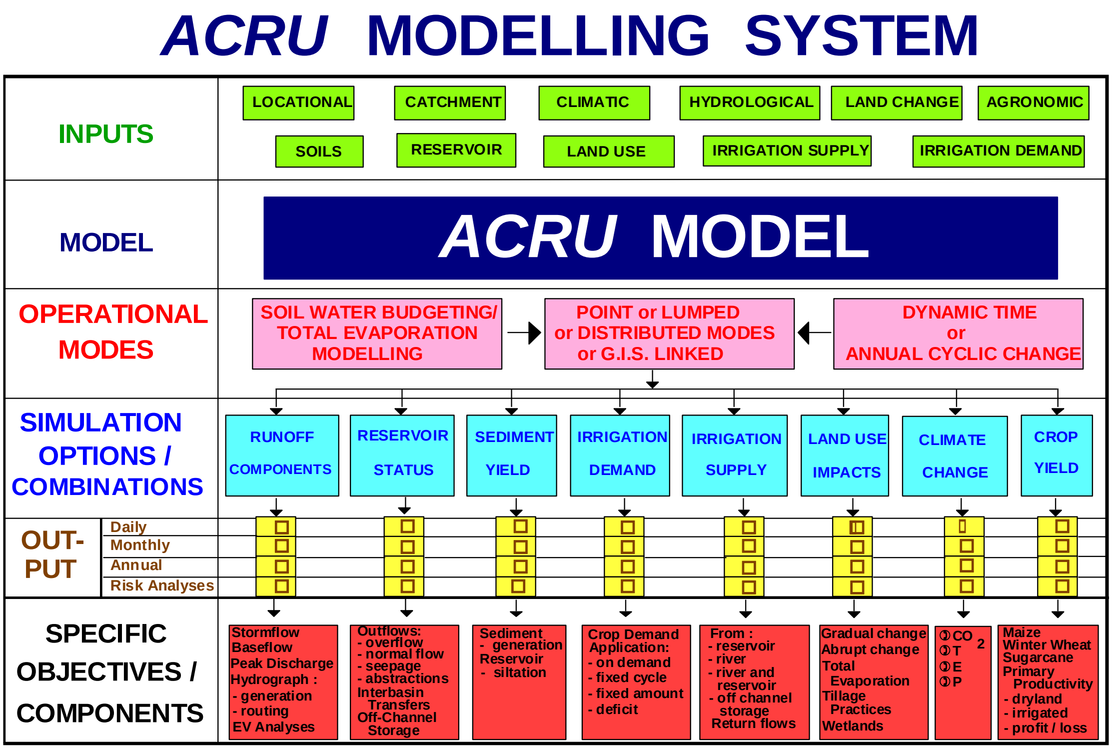


Figure 4.1 The *ACRU* agrohydrological modelling system (Schulze and Smithers, 1995a)

4.2.1 Stormflow volume

Stormflow is the runoff that is produced from a particular rainfall event, either at or close to the surface in a catchment, and which contributes to stream discharge within that catchment (Schulze, 2011). The response of a catchment to runoff from rainfall events depends on interactions between rainfall intensity, antecedent soil moisture conditions and land cover (Smithers *et al.*, 1996; Maher, 2000). Estimation of stormflow in the *ACRU* model is based on a modified SCS procedure which employs daily rainfall input as the driving mechanism (Schmidt *et al.*, 1987). The algorithm employed by the *ACRU* model in the estimation of stormflow is shown in Equation 4.1 (Schmidt *et al.*, 1987; Schulze, 1995).

$$Q_s = \frac{(P_g - I_a)^2}{(P_g - I_a + S)} \qquad for \qquad P_g > I_a \qquad (4.1)$$

where

Q_S = stormflow depth (mm),

P_g = gross daily precipitation amount (mm),

I_a = initial abstraction prior to stormflow commencement (mm), and

S = potential maximum soil water retention (mm).

The initial abstraction prior to stormflow commencement, I_a (mm) is a product of the coefficient of initial abstraction, (c) and potential maximum soil water retention (S), as shown in Equation 4.2.

$$I_a = cS \tag{4.2}$$

The storage capacity of a soil and the depth of the underlying layers impact on the timing and magnitude of the flood response to precipitation (Royappen, 2002). Hence, the lower the storage capacity and the shallower the subsurface soil depth limiting layers, the higher the potential flood magnitude and intensity. The effective depth of soil used in the *ACRU* model for stormflow generation (SMDDEP) attempts to account for various streamflow generating processes resulting from varrying climate, vegetation and soil conditions (Royappen, 2002). However, the SMDDEP variable is difficult to quantify and it has generally been estimated through experience/calibration, with default values suggested to the *ACRU* model user (Rowe, 2015).

4.2.2 Peak discharge

Peak discharge is an important variable in the estimation of sediment yield from a catchment (Schulze, 2011). The peak discharge from a given catchment is linked to the stormflow volume from that catchment, thus the accurate estimation of the stormflow volume is of prime importance in the determination of peak discharge (Schmidt and Schulze, 1984). The equation used in the simulation of peak discharge by the *ACRU* model from a catchment employs the SCS triangular-shaped unit hydrograph approach (Schulze and Schmidt, 1995) and it represents the stormflow hydrograph for an incremental unit depth of stormflow occurring in a unit increment of time as shown in Equation 4.3 (Schulze and Schmidt, 1995; Smithers *et al.*, 1996; Schulze *et al.*, 2004).

$$\Delta q_p = \frac{0.2083 A \Delta Q}{\frac{\Delta D}{2} + L} \quad (4.3)$$

where

Δq_p = peak discharge of incremental unit hydrograph ($m^3.s^{-1}$),

ΔQ = incremental storm flow depth (mm),

A = catchment area (km^2),

L = catchment lag time (h), and

ΔD = incremental time duration (h).

There are three options for estimating the catchment lag time in *ACRU* of which the Schmidt-Schulze lag equation is preferred for use within natural catchments in South Africa (Schmidt and Schulze, 1984; Schulze *et al.*, 1992). Preference for application of the Schmidt-Schulze lag equation in natural catchments in South Africa was based on verification studies which were acceptable. The catchment lag time, L (h) is determined from catchment area, A (km^2), 2-year return period 30-minute rainfall intensity, i_{30} ($mm.h^{-1}$), mean annual precipitation, *MAP* (mm), and average catchment slope, S (%), as shown in Equation 4.4 (Schmidt and Schulze, 1984).

$$L = \frac{A^{0.35} MAP^{1.1}}{41.67 S^{0.3} i_{30}^{0.87}} \quad (4.4)$$

The catchment lag time, L (h) is related to the catchment time of concentration, T_c (h) as shown in Equation 4.5 (Schulze and Schmidt, 1995).

$$L = 0.6 T_c \quad (4.5)$$

4.2.3 Sediment yield

Sediment yield in the *ACRU* model is simulated using the Modified Universal Soil Loss Equation (MUSLE) (Williams, 1975), which is an empirical equation derived from the Universal Soil Loss Equation (USLE) (Wischmeier and Smith, 1965; Wischmeier and Smith, 1978) through replacement of the rainfall erosivity factor with a storm flow factor (Lorentz and

Schulze, 1995). The MUSLE is used in the estimation of sediment yield arising from a specific storm event (Hui-Ming and Yang, 2009). The event sediment yield, Y_{sd} (t) is determined from stormflow volume for the event, Q_v (m^3), event peak discharge, q_p ($m^3.s^{-1}$), soil erodibility factor, K ($t.h.N^{-1}ha^{-1}$), slope length factor, L, slope steepness factor, S, cover management factor, C, supporting practices factor, P, and location specific MUSLE coefficients, α_{sy}, and β_{sy}, as shown in Equation 4.6 (Hui-Ming and Yang, 2009).

$$Y_{sd} = \alpha_{sy} (Q_v.q_p)^{\beta_{sy}} K.L.S.C.P \tag{4.6}$$

4.3 Data and Methods

A description of the materials and methods employed in this study are provided below.

4.3.1 Study area

The study area is located at La Mercy, 28 km north of Durban in South Africa on the site that now hosts the King Shaka International airport. The research catchments were established by the South African Sugarcane Research Institute (SASRI), formerly South African Sugar Experiment Station (SASEX), and were monitored under bare cover and various sugarcane management practices. There were four small catchments numbered from south to north (Platford and Thomas, 1985), with Catchment 101 the southernmost catchment and Catchment 104 the northernmost catchment (Maher, 1990). However, it was impossible to maintain all the four catchments completely and constantly under bare fallow conditions due to weeds and the catchments were occasionally ploughed (Platford and Thomas, 1985). The layout of the catchments is shown in Figure 4.2 and the catchment characteristics and soil types are summarised in Table 4.1 and Table 4.2 respectively.

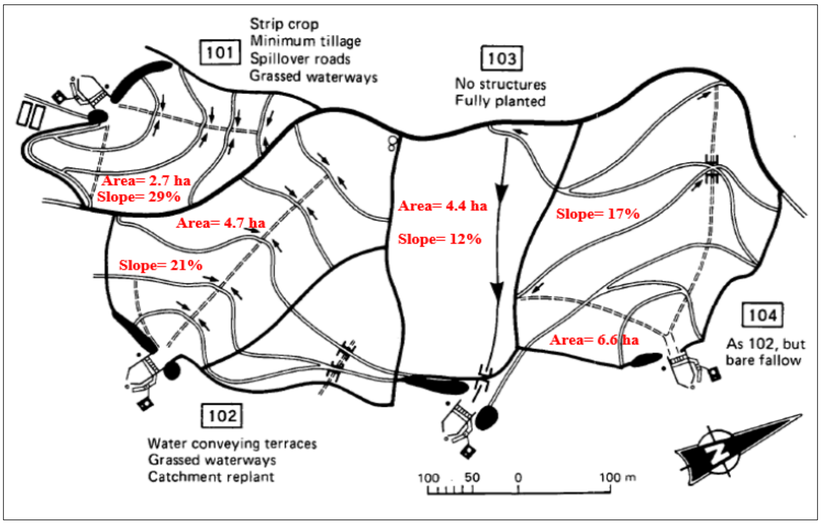


Figure 4.2 Layout of the La Mercy catchments, contour banks and waterways (after Platford and Thomas, 1985)

Table 4.1 Characteristics and management practices of the La Mercy catchments (after Platford and Thomas, 1985; Smithers *et al.*, 1996)

Location/ Practice	Catchment			
	101	102	103	104
Latitude (^{o},')	29^{o} 63' E	29^{o} 63' E	29^{o} 63' E	29^{o} 63' E
Longitude (^{o},')	31^{o} 07' S	31^{o} 07' S	31^{o} 07' S	31^{o} 07' S
Altitude/ Elevation (m)	75	75	90	80
Period of bare fallow	January 1978 to August 1984	January 1978 to August 1984	January 1978 to August 1984	January 1978 to December 1985
Period of sugarcane cover conditions	September 1984 to December 1995	September 1984 to December 1995	September 1984 to December 1995	January 1986 to December 1995
Method of land preparation	Minimum tillage[1]	Conventional tillage[2]	Conventional tillage[2]	Conventional tillage[2]

Location/ Practice	Catchment			
	101	102	103	104
Grass waterways	Yes	Yes	No, but had natural depression sown with *Eragrostis curvula* before planting	Yes

[1] Minimum tillage is the practice of reduced soil disturbance when the land is being prepared for planting (SASRI, 1998).

[2] Conventional tillage is the standard practice of ploughing with a disc, single or various disc harrows, a spike-tooth harrowing and surface planting (Morgan, 2005).

Table 4.2 Soil type distributions in the La Mercy catchments (after Platford and Thomas, 1985; Smithers *et al.*, 1996)

Soil form*	Soil series*	Soil code*	Soil Depth (m)	Area per catchment (%)			
				101	102	103	104
Hutton	Clansthal	Hu24	> 1.0	0	0	0	10
Arcadia	Rydalvale	Ar30	0.3 – 0.9	71	97	98	37
Swartland	Swartland	Sw31	0.1 – 0.6	29	3	2	53

*MacVicar *et al.* (1977)

4.3.2 Data

Daily observed rainfall and runoff depths, checked for errors with clarification of probable inconsistencies in the observed catchment data, and collated into the *ACRU* composite hydrometeorological data file format, was extracted from studies conducted by Smithers *et al.* (1996). Rainfall was continuously recorded by a centrally located intensity rain gauge whereas runoff was measured by type H flumes placed at the base of each catchment (Platford, 1979). As runoff passed through the measuring flume, depth readings were continuously recorded, hence, runoff intensity and amount could be recorded. On the other hand, sediment samplers were used to extract runoff samples at particular stages and analyses conducted to convert total sediment load and soil loss to tons per hectare. Some records from major storms resulting from cyclone Demoina in early 1984 and the September 1987 floods were lost due to equipment failure (Platford, 1988; Maher, 1990). Platford and Thomas (1985) and Maher (1990) further noted that sampling equipment were frequently washed away or completely silted up, thereby leading to a lack of records under bare fallow conditions, while Haywood (1991) noted that measuring equipment were poorly calibrated. Furthermore, storms which occurred after harvesting would cause residue to block the entrance of measuring flumes hence resulting in reduced flows captured by the collecting tanks. Theft and vandalism of the rainfall intensity gauges was also a big problem and a number of records from the automatic recorders were affected (Maher, 1990). In addition, various sediment yield records were incomplete and Maher (1990) only analysed four events of complete sediment yield records.

The available data comprises daily observed rainfall and runoff for the period 1978 – 1995, peak discharge for the period 1984 – 1995 and daily maximum and minimum temperature and A-pan data for the period 1978 – 1995. Historical information on the management practices at the La Mercy catchments for the period 1978 – 1988 was also obtained from studies reported by Haywood (1991).

4.3.3 Model verification and performance

Smithers *et al.* (1996) used Equations 4.1, 4.3 and 4.6 embedded in the *ACRU* model to simulate stormflow, peak discharge and sediment yield, respectively, from the La Mercy catchments under bare fallow conditions and sugarcane production. The *ACRU* model was found to be generally suitable in the investigation of the effect of sugarcane production on water resources, despite some inadequacies in the simulation of stormflow, peak discharge and sediment yield. As part of the verification undertaken in this study, daily rainfall was further quality controlled and used as input into the *ACRU* model to simulate stormflow, peak discharge and sediment yield and the results compared against respective observed events that were considered to be reliable. Inconsistencies in the records that were excluded from verifications included events with:

(a) runoff volumes equal to zero but with rainfall greater than or equal to 25 mm,
(b) rainfall depth equal to zero but runoff volume greater than zero,
(c) peak discharge values for which either rainfall depth or runoff volume was missing, and
(d) sediment yield records for which no runoff volume was available.

The inconsistent events are listed in Appendix 3.1 to Appendix 3.3 in Chapter 3 while the methodology used in model verification is presented in Sections 4.3.3.1 to 4.3.3.3.

4.3.3.1 Simulation and verification of daily runoff volume

The *ACRU* variables used in the simulation of runoff volume from the La Mercy catchments were obtained from Smithers *et al.* (1996) and the Sugarcane Decision Support System (SCDSS) documented in the same report. The SCDSS incorporates knowledge gained from modelling hydrology from sugarcane land covers under different management practices. The relevant *ACRU* variables are shown in Appendix 4.1 and runoff simulated using Equation 4.1. The performance of the *ACRU* model was then assessed by comparing the simulated runoff depth to the observed runoff depth.

4.3.3.2 Simulation and verification of daily peak discharge

In this study, Type 2 rainfall intensity distribution (Schulze *et al.*, 2004) was used as the study site is located in the Type 2 rainfall temporal distribution region and simulation of daily peak discharge was conducted using the SCS triangular-shaped incremental unit hydrograph approach shown in Equation 4.3. Weddepohl (1988) determined four general types of rainfall intensity distribution for southern Africa namely Type 1, 2, 3 and 4 with Type 1 the least intense and Type 4 the most intense. The lag time was estimated using the Schmidt-Schulze lag equation shown in Equation 4.4 and the SCS method (Schulze and Schmidt, 1995) and these lag times were converted into time of concentration (T_c), as shown in

Table 4.3. Simulated runoff volume obtained using Equation 4.1 was used as input to simulate peak discharge. The simulated peak discharge values were then verified through comparisons with observed peak discharges.

Table 4.3 Estimated time of concentration

Catchment	Time of concentration using Schmidt-Schulze lag equation (h) (Schmidt and Schulze, 1984)	Time of concentration using hydraulic principles (h) (Schulze and Schmidt, 1995)	Time of concentration using SCS method (h) (Schulze and Schmidt, 1995)
101	0.94	1.91	1.01
102	1.26	2.20	1.58
103	1.45	1.64	1.73
104	1.51	2.50	1.63

4.3.3.3 Simulation and verification of daily sediment yield

Simulation of daily sediment yield was driven by the simulated stormflow volumes and simulated peak discharges using Equation 4.6 embedded in the *ACRU* model. The various MUSLE parameters (*i.e.* *K*, *L*, *S* and *P*) representing conditions and practices at the La Mercy catchments were estimated wherever possible using an appropriate level of data requirement, as outlined by Lorentz and Schulze (1995), while the dynamic *C* factors were obtained from Smithers *et al.* (1996). Three options in the *ACRU* model namely Level 1, 2 and 3 are available for the estimation of MUSLE parameters. Level 1 input option is appropriate whenever limited information on a catchment or practice is available while Level 3 option is suitable for instances when detailed information is available. The *K* factor was estimated using the Level 1 input option which determines the soil erodibility class from the binomial classification of the soil. The *LS* factor was also estimated using the Level 1 input option (limited information on catchment available) which relates the *LS* factor to the slope gradient, and the *P* factor was estimated using the Level 3 input option which takes into account contouring, strip cropping, terracing and subsurface drainage. The *C* factors were taken from studies conducted by Smithers *et al.* (1996) with the assumption that the *C* factor for sugarcane at full canopy was 0.01 and after harvesting it was 0.60, and that full canopy is achievable in five months for cane harvested in the summer months and six months for cane harvested during winter. These are based on Smithers *et al.* (1996) who used expert opinion and calibrations from measured values of sediment yield at various runoff plots in selection of realistic sugarcane dynamic *C* factors. This approach is documented by Tanyaş *et al.* (2015) as one of the methods of estimating *C* factors. The *K* factors were area-weighted according to soil properties and area covered. *C* factors were dynamically varied according to the stage of growth and harvesting practise and constant *LS* and *P* factors were employed since they do not vary over time. The parameters used in the simulation of sediment yield are shown in Appendix 4.2 while the dynamically varying cover factors (*C*) for sugarcane are shown in Table 4.4.

Table 4.4 The cover management factor (*C*) for sugarcane (after Smithers et al., 1996)

C factor	Months after planting											
	1	2	3	4	5	6	7	8	9	10	11	12
Summer	0.60	0.30	0.10	0.05	0.02	0.01	0.01	0.01	0.01	0.01	0.01	0.01
Winter	0.60	0.40	0.30	0.10	0.04	0.02	0.01	0.01	0.01	0.01	0.01	0.01

4.4 Results and Discussion

In this section, the results of simulations and verification of runoff, peak discharge and sediment yield for the La Mercy catchments are presented and discussed.

4.4.1 Verification of runoff volume

A discussion of runoff verification under both bare fallow and sugarcane cover conditions is contained below. The parameters used in the verification were obtained as outlined above.

4.4.1.1 Bare fallow conditions

A discussion of runoff verification results under bare fallow conditions for each of the La Mercy catchments is presented below.

4.4.1.1.1 Catchment 101

Daily rainfall and accumulated daily runoff under bare fallow conditions from Catchment 101 are presented in Figure 4.3 while the simulated vs observed, and frequency distribution plots are shown in Figure 4.4 (a) and Figure 4.4 (b) respectively. The linear regression statistics which indicate how well the daily stormflow depth was simulated are shown in Figure 4.4 (a).

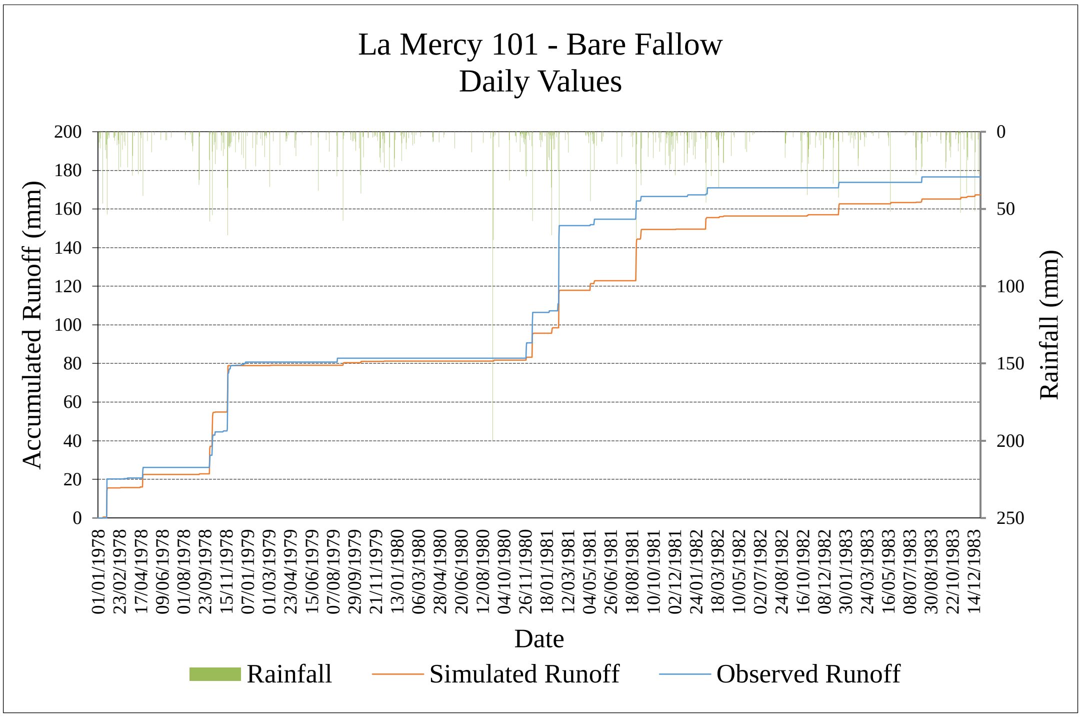
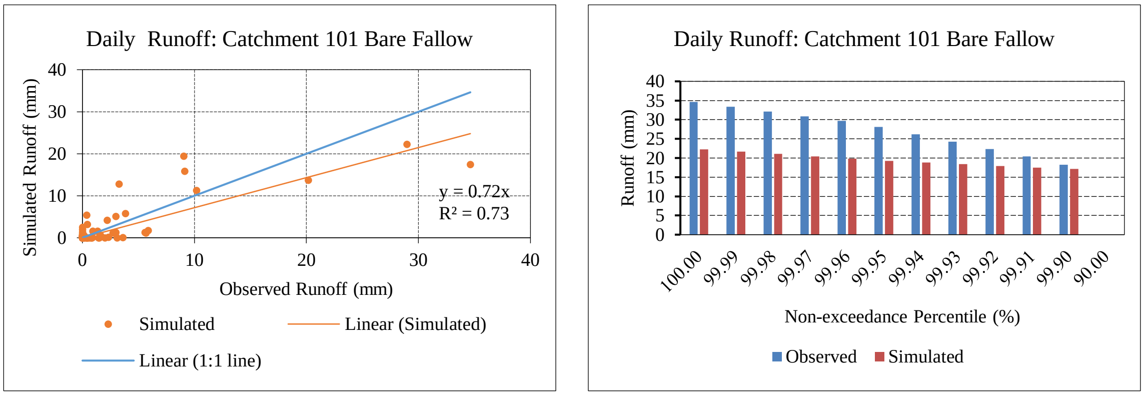


Figure 4.3 Daily rainfall and runoff simulated with the SCDSS: Catchment 101, bare fallow conditions



(a) (b)

Figure 4.4 (a) Simulated vs observed and (b) frequency distribution plots: Daily runoff depths simulated from Catchment 101 under bare fallow cover

As shown in Figure 4.3, simulation of runoff from Catchment 101 under bare fallow conditions resulted in an overall under simulation of 5.5 % over the period simulated which is generally good. In addition, the scatter around the 1:1 line was relatively good with runoff generally under simulated as indicated in Figure 4.4 (a) and Figure 4.4 (b). It is hypothesised that the general under simulation of runoff could be due to a random error in the measurement of large runoff volumes and the fact that the *ACRU* model is not an optimising model.

4.4.1.1.2 Catchment 102

Catchment 102 daily rainfall and accumulated daily runoff under bare fallow conditions are shown in Figure 4.5 while the simulated vs observed plots with the regression statistics and the frequency distribution plots are shown in Figure 4.6 (a) and Figure 4.6 (b) respectively.

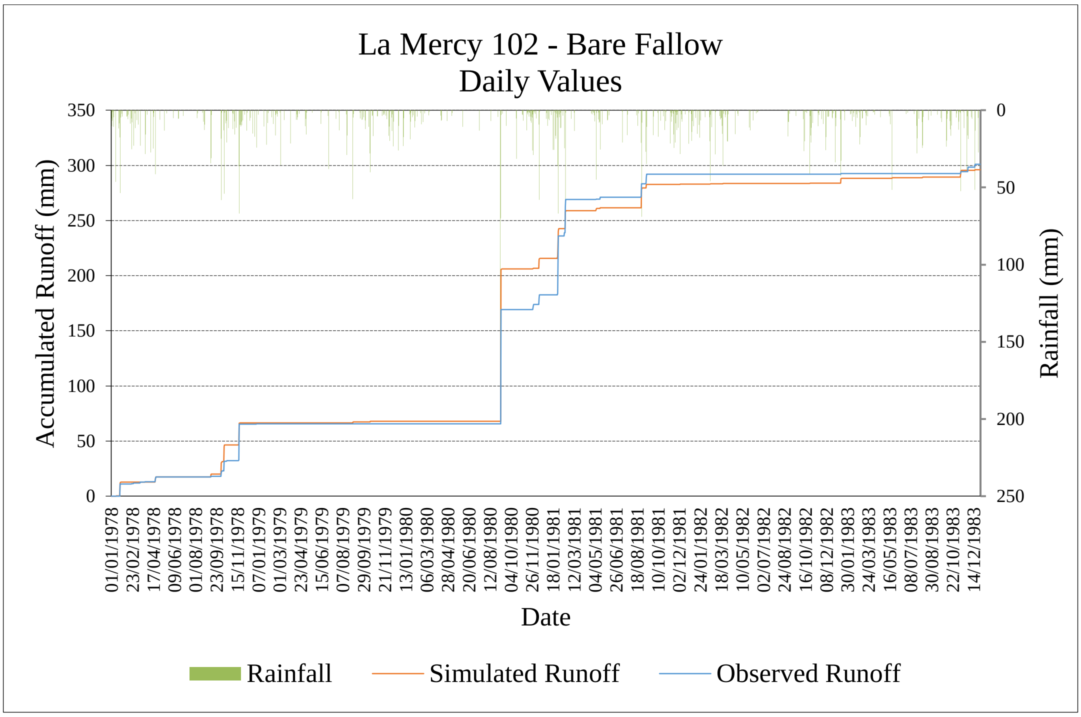
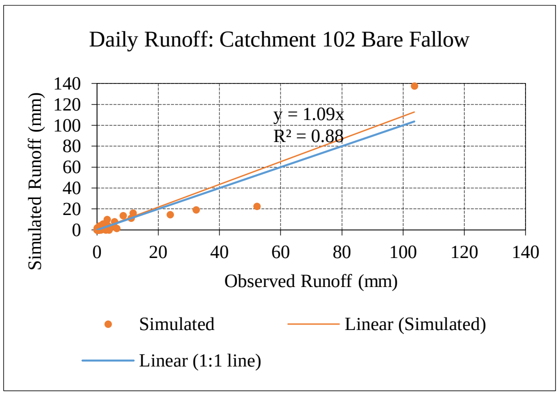
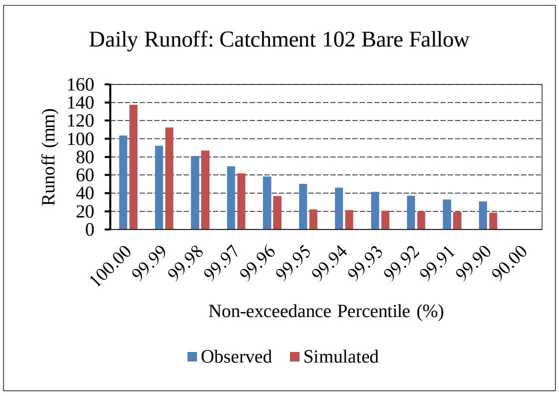


Figure 4.5 Daily rainfall and runoff simulated with the SCDSS: Catchment 102, bare fallow conditions





(a) (b)

Figure 4.6 (a) Simulated vs observed and (b) frequency distribution plots: Daily runoff volumes simulated from Catchment 102 under bare fallow cover

For Catchment 102 under bare fallow conditions, runoff simulation was generally good and resulted in an overall under simulation of 1.6 % as shown in Figure 4.5. Additionally, the runoff relative sequences and orders of magnitude were reasonably simulated as shown in the same figure and the simulations were acceptable as shown by the regression statistics in Figure 4.6 (a), and large runoff volumes were generally over simulated while small runoff volumes were under simulated as shown in Figure 4.6 (b). The over and under simulations could be attributed to random errors in the measurement of daily runoff volumes and the structure of the *ACRU* model which is not parameter fitting.

4.4.1.1.3 Catchment 103

The daily rainfall and accumulated daily runoff for Catchment 103 under bare fallow conditions are shown in Figure 4.7 while the linear regression plots with the statistics and the frequency distribution plots are shown in Figure 4.8 (a) and Figure 4.8 (b) respectively.

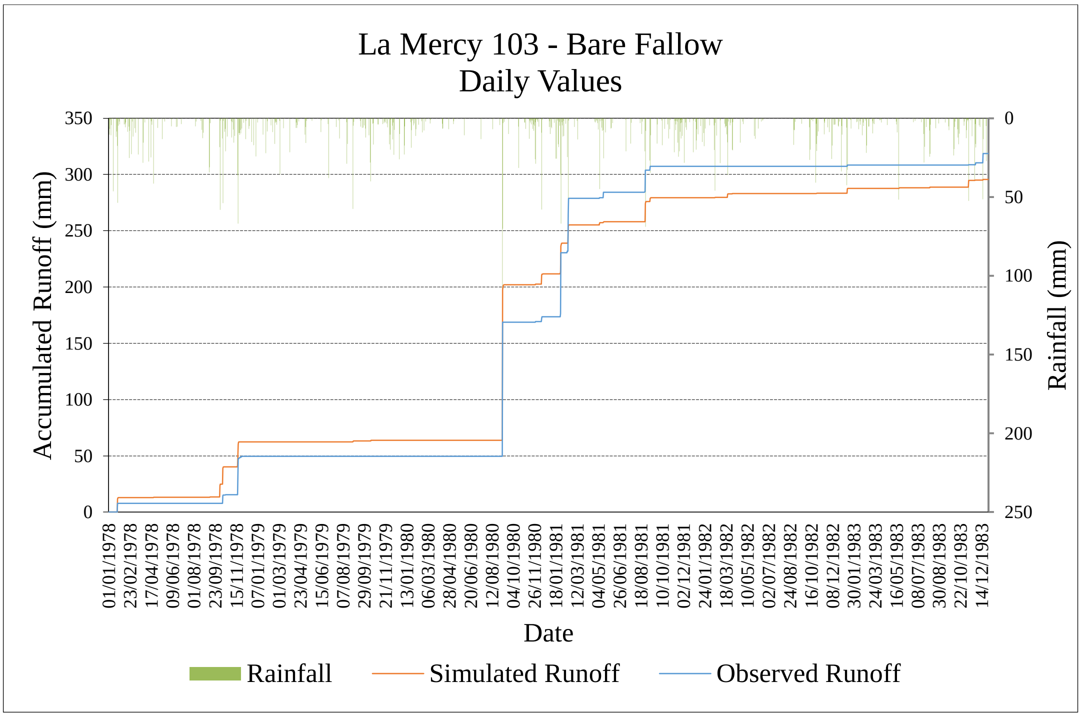
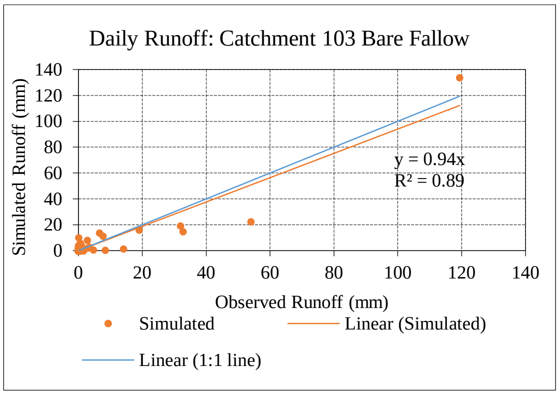
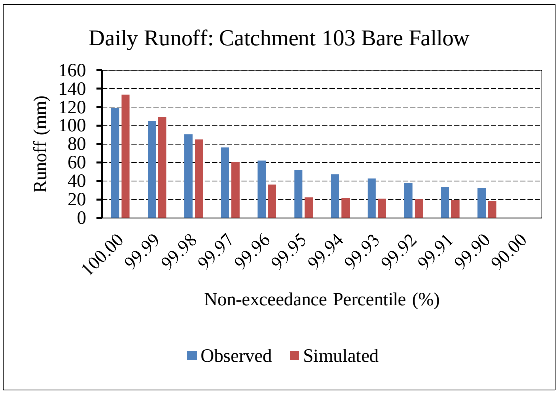


Figure 4.7 Daily rainfall and runoff simulated with the SCDSS: Catchment 103, bare fallow conditions



(a)



(b)

Figure 4.8 (a) Simulated vs observed and (b) frequency distribution plots: Daily runoff volumes simulated from Catchment 103 under bare fallow cover

From Figure 4.6, it is evident that the simulation resulted in an overall under simulation of 7.8 % which is good. Furthermore, an acceptable model fit between observed and simulated daily runoff exists as shown by the regression statistics in Figure 4.8 (a), and the large daily runoff volumes were over simulated while the small runoff volumes were under simulated as shown in Figure 4.8 (b). Similar to Catchment 102, the over and under simulations could be attributed to random errors in the measurement of daily runoff volumes and the fact that the *ACRU* model is not an optimising model.

4.4.1.1.4 Catchment 104

The daily rainfall and accumulated daily runoff for Catchment 104 under bare fallow conditions are shown in Figure 4.9 while the simulated vs observed plots together with the regression statistics and the frequency distribution plots are shown in Figure 4.10 (a) and Figure 4.10 (b) respectively.

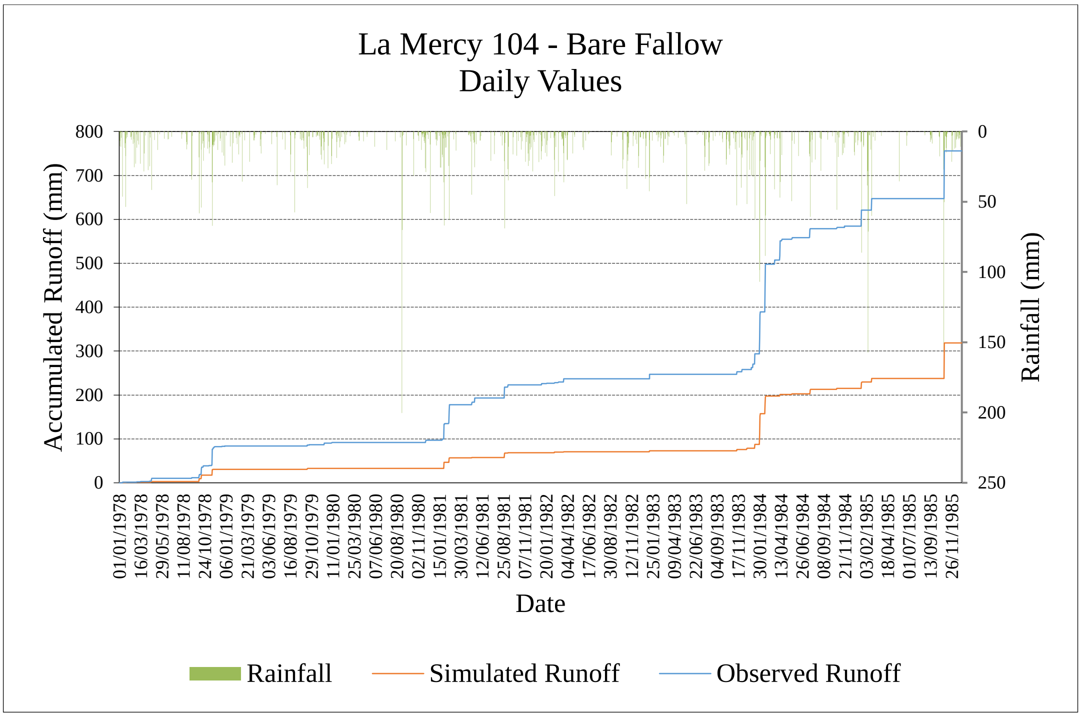
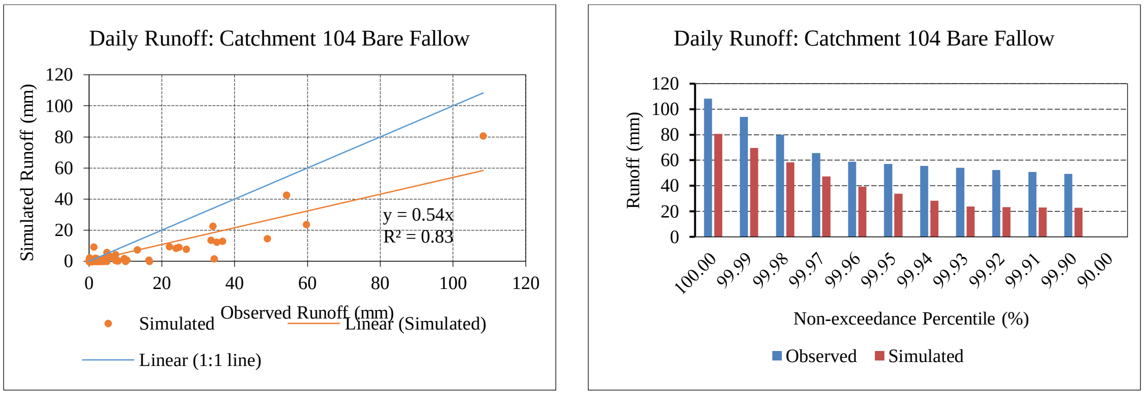


Figure 4.9 Daily rainfall and runoff simulated with the SCDSS: Catchment 104, bare fallow conditions



(a) (b)

Figure 4.10 (a) Simulated vs observed and (b) frequency distribution plots: Daily runoff volumes simulated from Catchment 104 under bare fallow cover

As shown in Figure 4.9, runoff simulation resulted in a consistent under simulation. and the scatter around the 1:1 line was very poor, although the scatter around the fitted line was good as shown by the regression statistics in Figure 4.10 (a), and runoff depth was consistently under simulated as shown in Figure 4.10 (b). It was initially suspected that the consistent under simulation could be attributed to the soil variables and parameter selections shown in Appendix 4.1, but a further review of the parameters showed they were justifiably selected. Further comparisons between observed and simulated runoff volumes showed that runoff was generally under simulated by 64 %. Hence, it is suspected that the general under simulation of runoff could be due to a systematic error in the measurement of runoff volumes caused by poor calibration of measuring equipment as documented by Haywood (1991). Furthermore, the under simulations could be attributed to the fact that the *ACRU* model is not a parameter fitting model. Scaling the observed runoff by a factor of 64% greatly improved the verifications as shown in Figure 4.11.

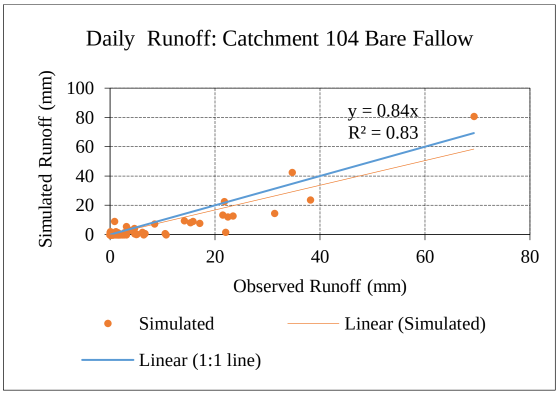


Figure 4.11 Daily runoff volumes simulated from Catchment 104 under bare fallow cover with observed runoff scaled by a factor of 64 %

4.4.1.2 Sugarcane cover conditions

The discussion of runoff verification results under sugarcane cover conditions for each of the La Mercy catchments are presented below.

4.4.1.2.1 Catchment 101

Catchment 101 daily rainfall and accumulated daily runoff under sugarcane land cover are shown in Figure 4.12 while the linear regression plots with the statistics and the frequency distribution plots are shown in Figure 4.13 (a) and Figure 4.13 (b) respectively.

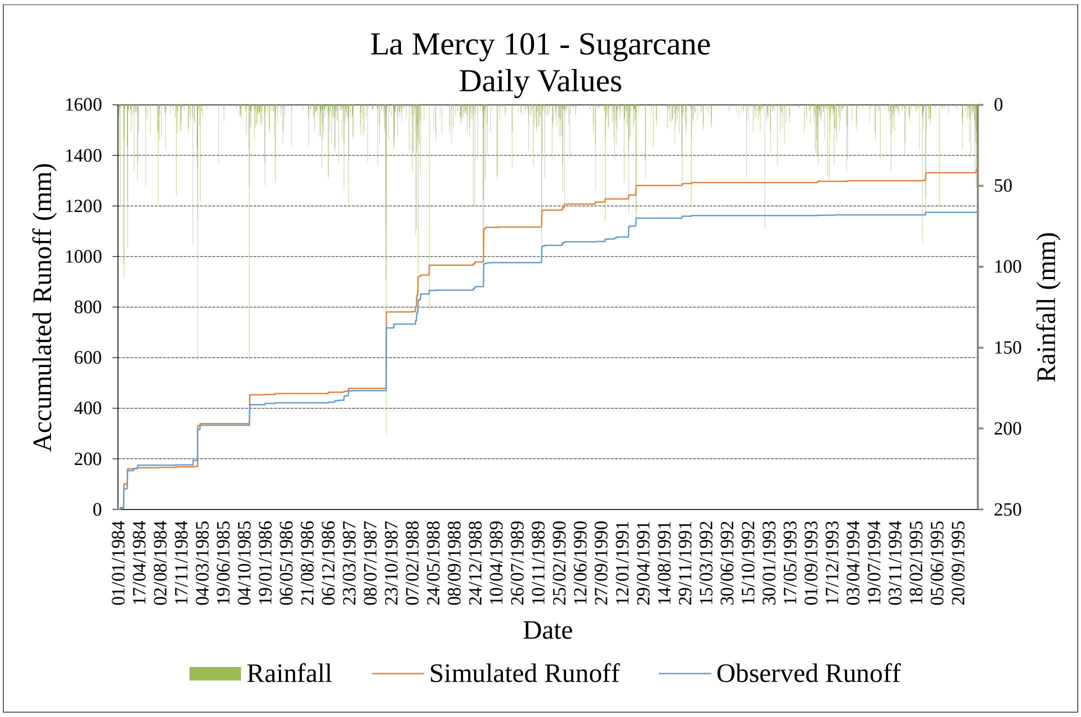
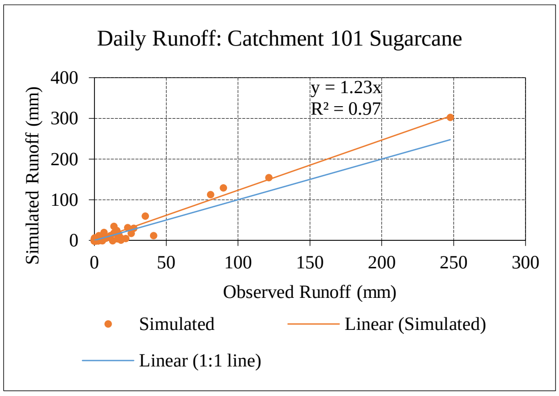
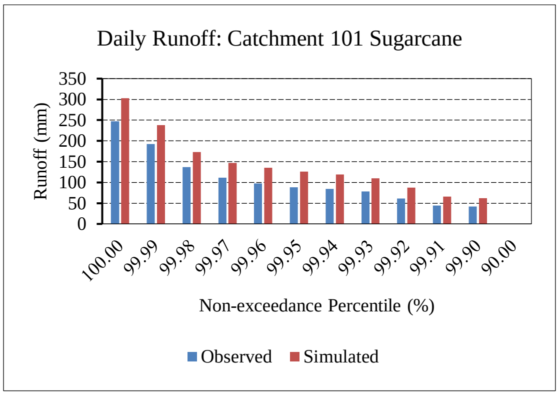


Figure 4.12 Daily rainfall and runoff simulated with the SCDSS: Catchment 101, sugarcane cover conditions



(a)



(b)

Figure 4.13 (a) Simulated vs observed and (b) frequency distribution plots: Daily runoff volumes simulated from Catchment 101 under sugarcane cover

Generally, runoff simulated from Catchment 101 resulted in an over simulation for the period as shown in Figure 4.12 and represents an overall over simulation of 14.5 %. The association between observed and simulated runoff was acceptable as indicated by the regression statistics in Figure 4.13 (a) and runoff was consistently over simulated as shown by the frequency plots in Figure 4.13 (b). The general over simulation of runoff volume could be attributed to random errors in the measurement of daily runoff volumes and the structure of the *ACRU* model which is not parameter fitting.

4.4.1.2.2 Catchment 102

Catchment 102 daily rainfall and accumulated daily runoff under sugarcane land cover are shown in Figure 4.14 while the linear regression plots together with the statistics and the frequency distribution plots are shown in Figure 4.15 (a) and Figure 4.15 (b) respectively.

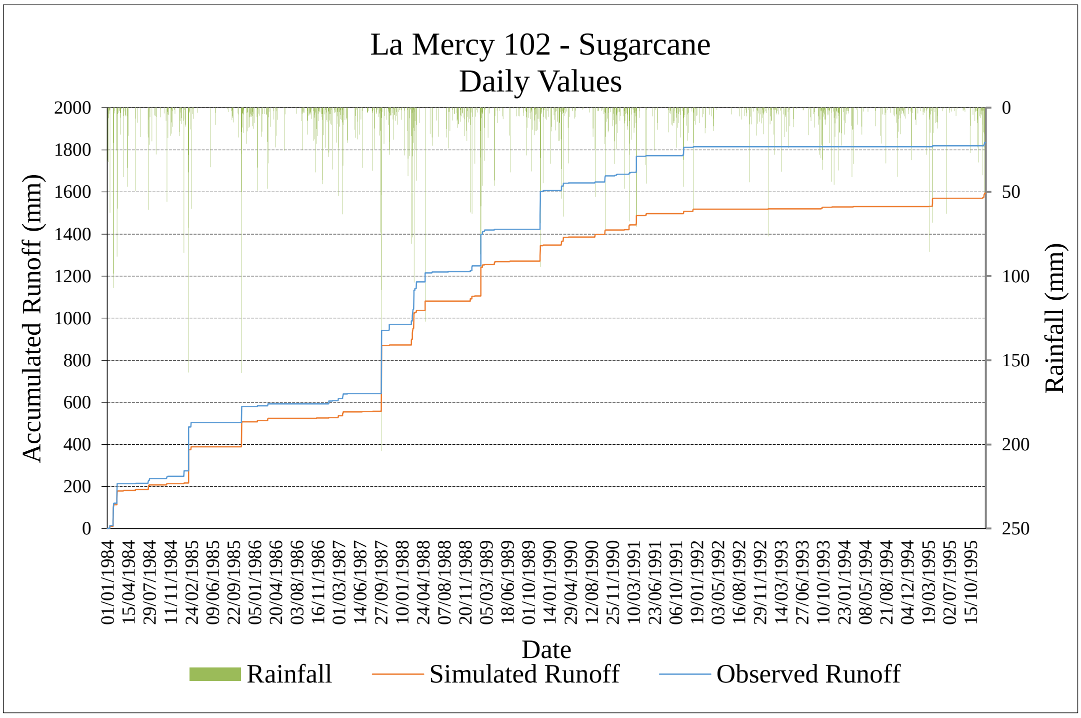
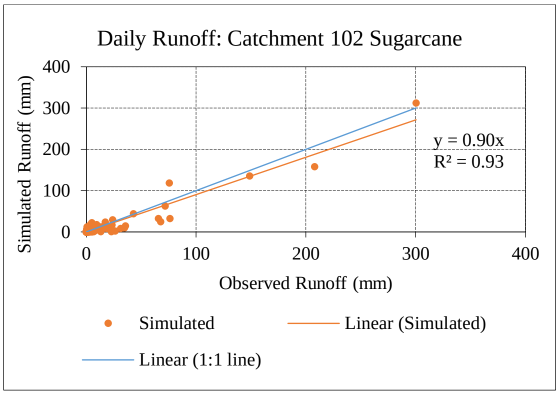
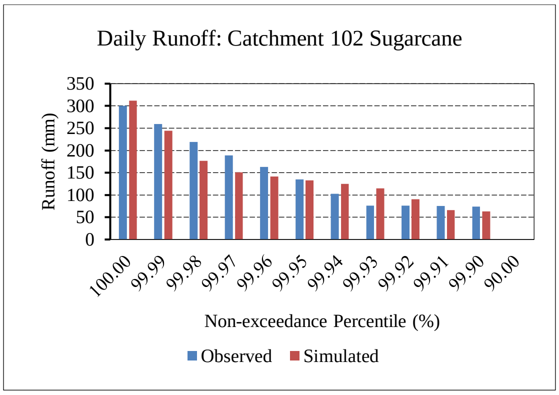


Figure 4.14 Daily rainfall and runoff simulated with the SCDSS: Catchment 102, sugarcane cover conditions



(a)



(b)

Figure 4.15 (a) Simulated vs observed and (b) frequency distribution plots: Daily runoff volumes simulated from Catchment 102 under sugarcane cover

Simulation of daily runoff generally resulted in a close relationship between observed and simulated runoff as shown in Figure 4.14 and gave rise to an overall under simulation of 13.1 %. The general scatter of the simulated runoff around the 1:1 line is also acceptable as indicated by the regression statistics in Figure 4.15 (a) with some under and over simulations as shown in Figure 4.15 (b). The under and over simulation of runoff volumes could be attributed to similar reasons cited under Section 4.4.1.2.1.

4.4.1.2.3 Catchment 103

Catchment 103 daily rainfall and accumulated daily runoff under sugarcane land cover are shown in Figure 4.16 while the linear regression plots and statistics, and the frequency distribution plots are shown in Figure 4.17 (a) and Figure 4.17 (b) respectively.

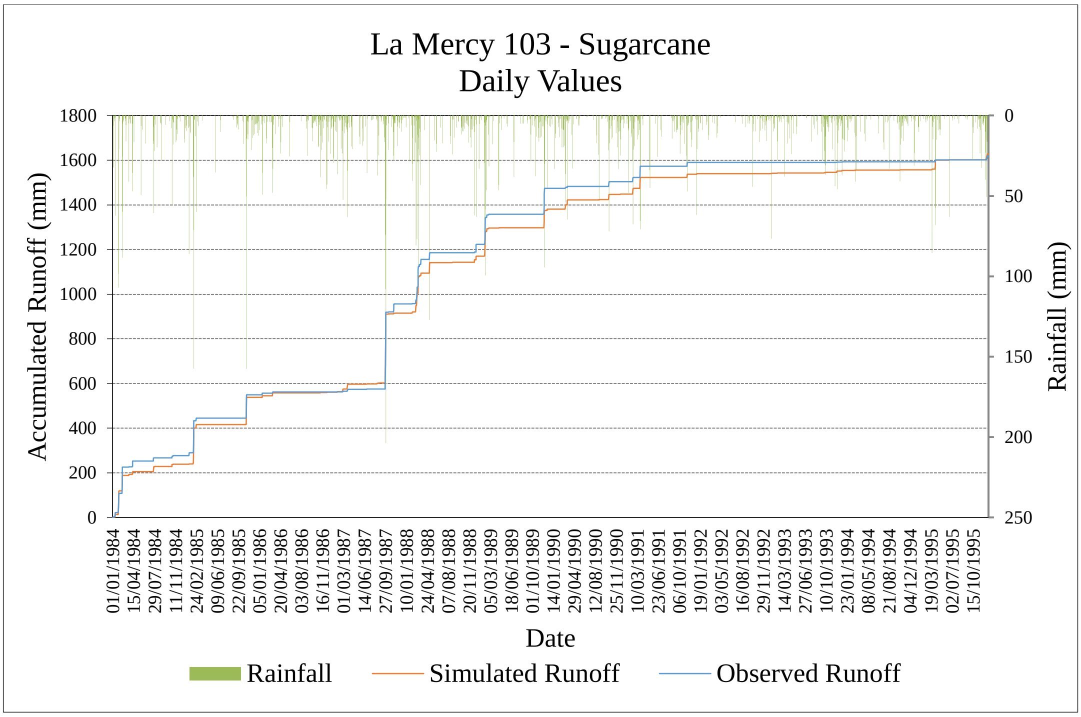
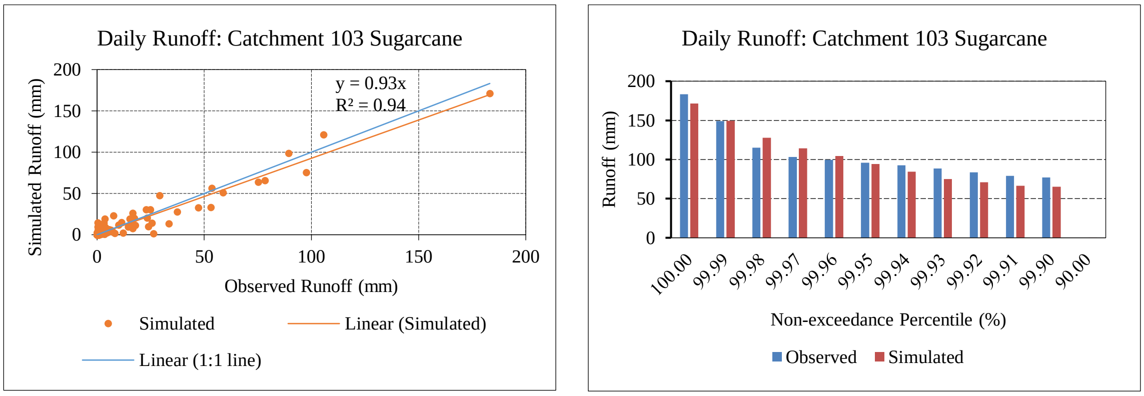


Figure 4.16 Daily rainfall and runoff simulated with the SCDSS: Catchment 103, sugarcane cover conditions



(a) (b)

Figure 4.17 (a) Simulated vs observed and (b) frequency distribution plots: Daily runoff volumes simulated from Catchment 103 under sugarcane cover

Runoff simulation generally gave rise to an over simulation for the period as shown in Figure 4.16, with an overall over simulation of 0.5 %. In addition, the general plot around the 1:1 line is acceptable as indicated by the regression statistics in Figure 4.17 (a) and the frequency distribution closely related as shown in Figure 4.17 (b). However, both under and over simulations exist and this could be attributed to the same reasons discussed under Section 4.4.1.2.1.

4.4.1.2.4 Catchment 104

Catchment 104 daily rainfall and accumulated daily runoff under sugarcane land cover are shown in Figure 4.18 while the linear regression plots and statistics, and the frequency distribution plots are shown in Figure 4.19 (a) and Figure 4.19 (b) respectively.

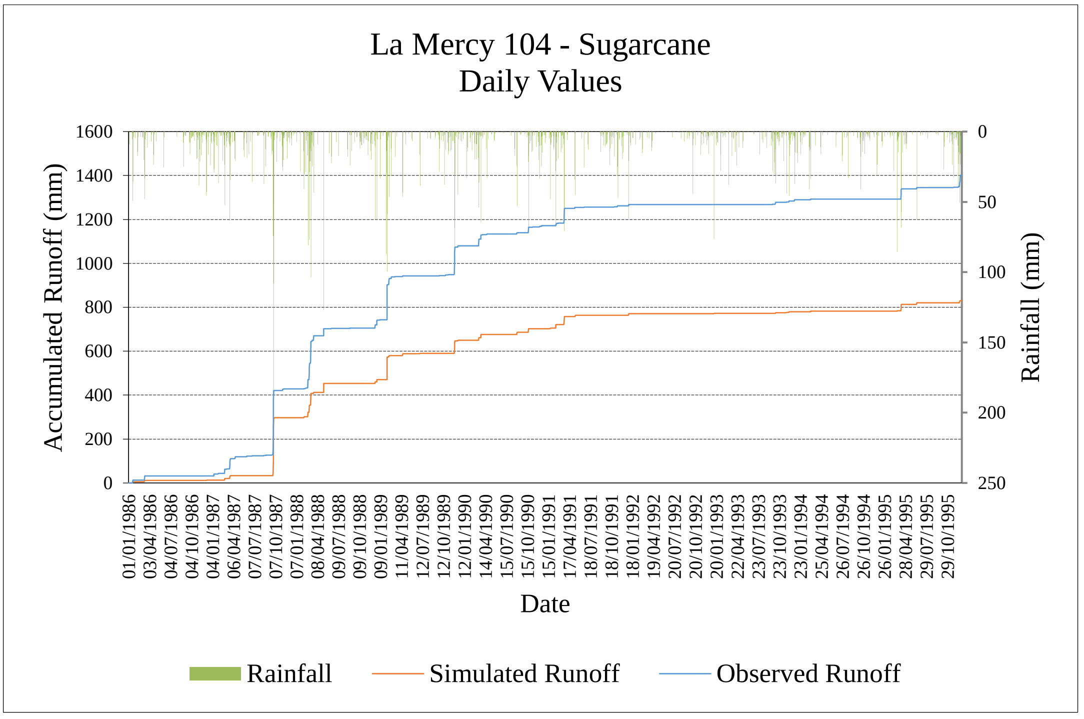
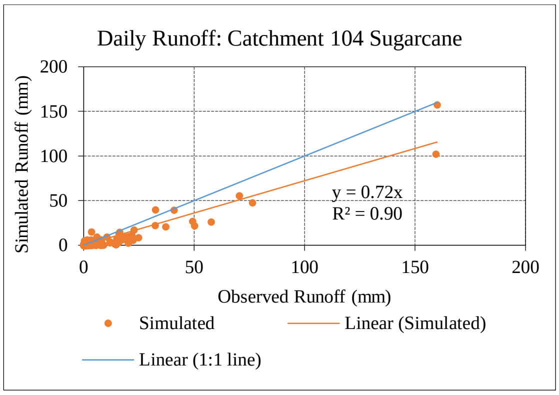
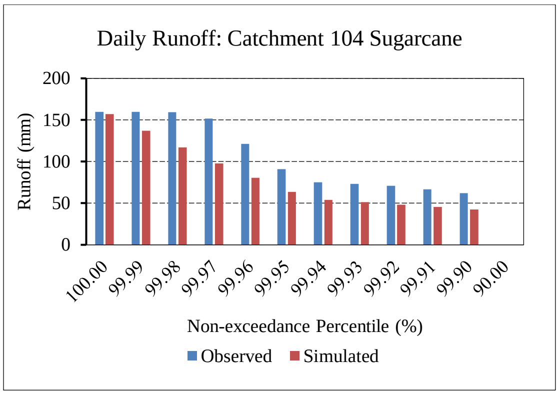


Figure 4.18 Daily rainfall and runoff simulated with the SCDSS: Catchment 104, sugarcane cover conditions



(a)



(b)

Figure 4.19 (a) Simulated vs observed and (b) frequency distribution plots: Daily runoff volumes simulated from Catchment 104 under sugarcane cover

Use of the SCDSS parameters to simulate runoff resulted in a consistent under simulation with an overall under simulation of 40.8 % as shown in Figure 4.18. The general plot around the 1:1 line was poor although the scatter around the fitted line was good as shown by the regression statistics in Figure 4.19 (a) and runoff was consistently under simulated as shown in Figure 4.19 (b). The consistent under simulation could be attributed to a systematic error in the measurement of runoff volumes caused by poor calibration of measuring equipment as documented by Haywood (1991) and the fact that the *ACRU* model is not an optimising model. Similar to bare fallow conditions, calibration of the observed runoff by a factor of 64% greatly improved the verifications as shown in Figure 4.20.

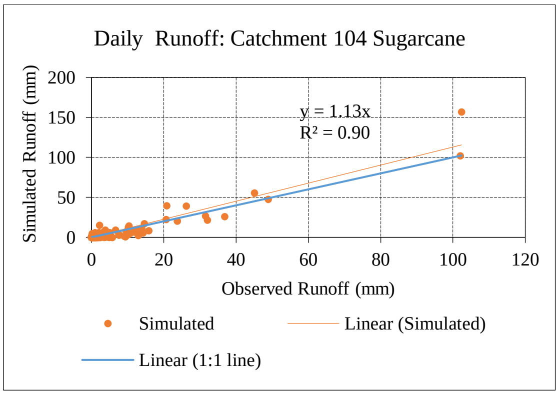


Figure 4.20 Daily runoff volumes simulated from Catchment 104 under sugarcane cover with observed runoff scaled by a factor of 64 %

4.4.2 Verification of daily peak discharge

Verification of daily peak discharge was only conducted under sugarcane land cover since there was no observed peak discharge data available under bare fallow conditions. The results are summarised and presented in Figure 4.21.

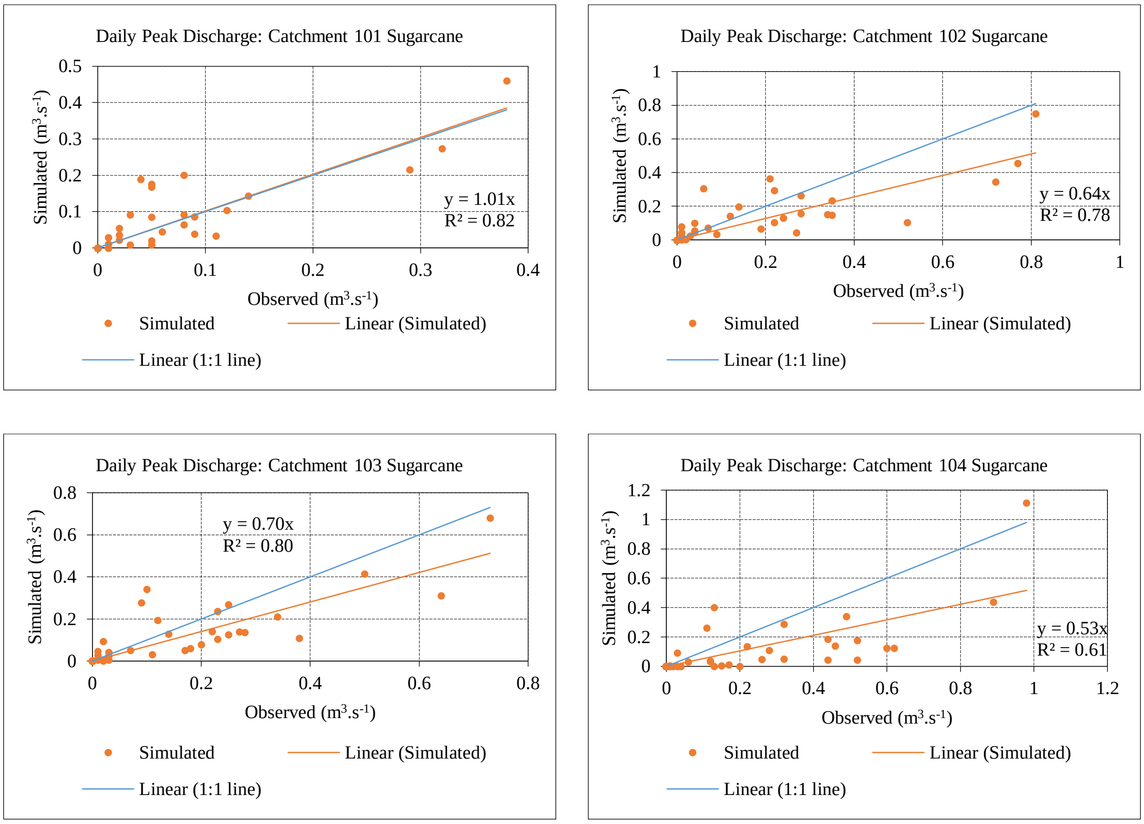


Figure 4.21 Daily peak discharge simulated using observed daily rainfall, simulated stormflow volumes and estimated catchment times of concentration with the Schmidt-Schulze lag equation

The trends exhibited by simulated peak discharges shown in Figure 4.21 are related to trends exhibited by simulated runoff volumes under each catchment and this confirms that runoff volume is a driver to peak discharge. Furthermore, the association between observed and simulated peak discharge across all four catchments is reasonably good as indicated by the regression statistics in Figure 4.21, and the trends in frequency distribution of simulated and observed peak discharge are also closely associated as shown in Figure 4.22. Similar to runoff volume trends, the under and over simulations of peak discharge could be attributed to random errors in the measurement of daily runoff and hence daily peak discharge values and the fact that *ACRU* model is not parameter fitting. Furthermore, it is possible that calibration problems of the flumes used for measuring peak discharge existed.

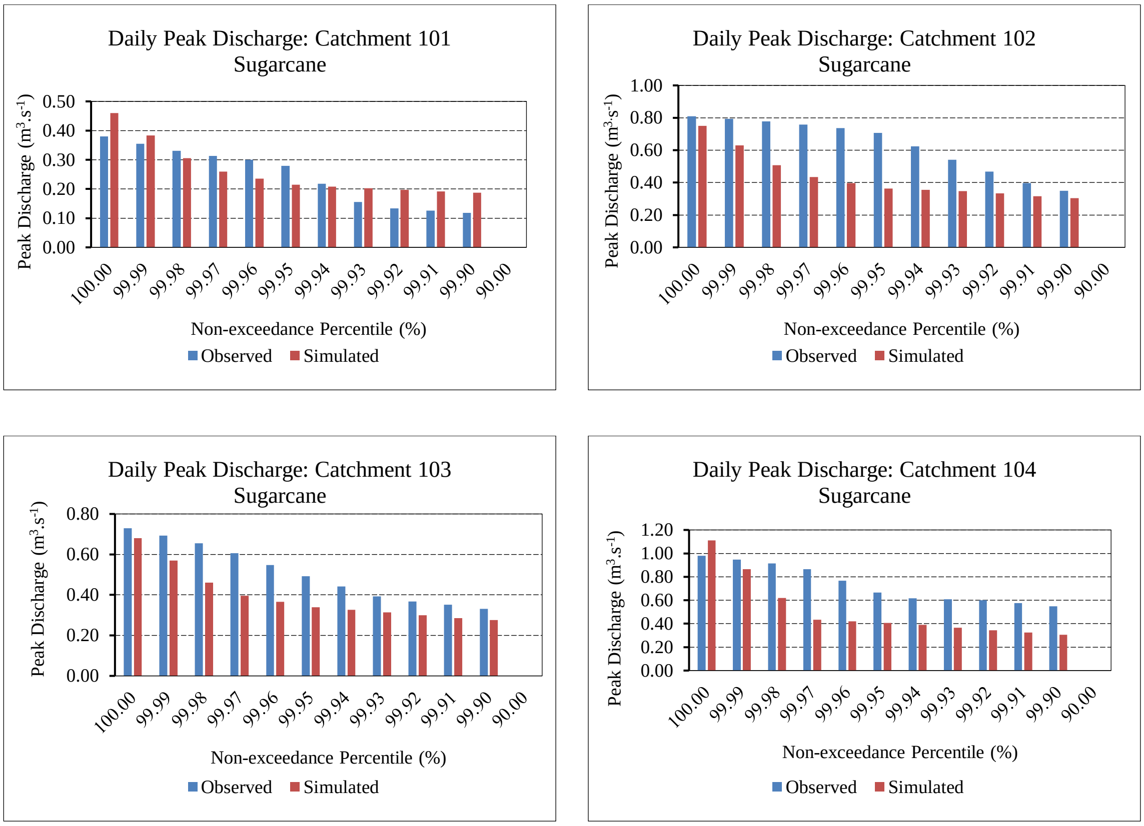


Figure 4.22 Frequency analysis of daily peak discharge for catchments 101, 102, 103 and 104

4.4.3 Verification of daily sediment yield

Similar to daily peak discharge, daily sediment yield was verified under sugarcane land cover conditions since there was no observed sediment yield data available under bare fallow conditions. Considering that many sediment yield records were incomplete, only events documented by Maher (1990) together with a few events where the observed data were considered to be consistent were used in the verifications. The results are presented in Figure 4.23 and the discussions follow thereafter.

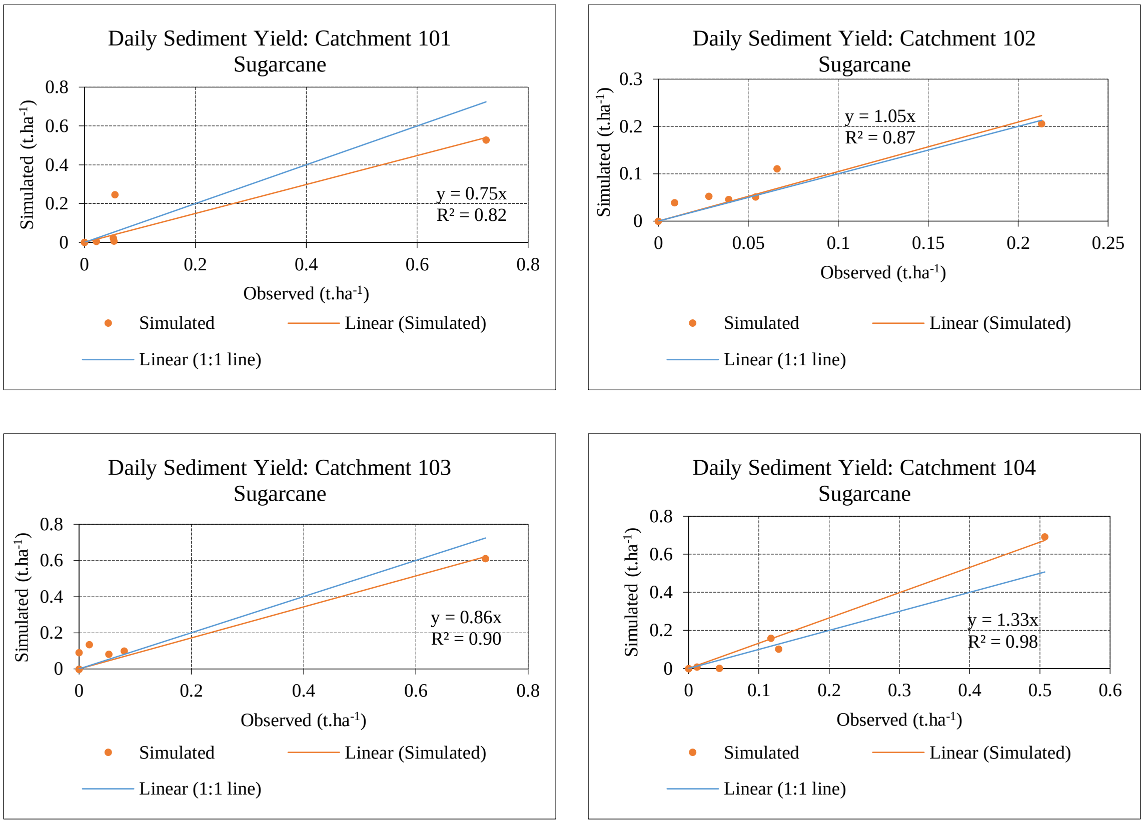


Figure 4.23 Daily sediment yield simulated from the La mercy catchments

The correlation between simulated and observed sediment yield events was reasonably good as shown by the regression statistics in Figure 4.23 and the events used in the verication are shown in Appendix 4.3.

4.5 Conclusions

Generally, the relative sequences and orders of magnitude of runoff from the La Mercy catchments were reasonably simulated under both bare fallow and sugarcane land cover conditions. In addition, the correlation between observed and simulated runoff volumes were reasonably good as depicted by the regression statistics shown in Table 4.5. However, over and under simulations were evident and these could be attributed to random errors in the measurement of daily runoff volumes and the fact that the *ACRU* model is not an optimising model, except for Catchment 104 under both bare fallow and sugarcane land cover conditions where it is suspected that systematic errors could have occurred in the measurement of daily runoff volumes.

Table 4.5 Regression statistics for simulated vs observed runoff, peak discharge and sediment yield

Variable	Catchment 101		Catchment 102		Catchment 103		Catchment 104	
	Slope of regression line	R^2	Slope of regression line	R^2	Slope of regression line	R^2	Slope of regression line	R^2
Runoff (BF)	0.72	0.73	1.09	0.88	094	0.89	0.54	0.83
Runoff (SP)	1.23	0.97	0.90	0.93	0.93	0.94	0.72	0.90
Peak Discharge (SP)	1.01	0.82	0.64	0.78	0.70	0.80	0.53	0.61
Sediment Yield (SP)	0.75	0.82	1.05	0.87	0.86	0.90	1.33	0.98

*Key:

(BF) Bare fallow value of the variable

(SP) Value of the variable during sugarcane production

Simulation and verification of peak discharge was only conducted under sugarcane land cover because there was no observed peak discharge data available under bare fallow conditions. The trends exhibited by simulated daily peak discharges were similar to trends exhibited by simulated daily runoff volumes under each catchment thereby confirming that runoff volume drives peak discharge. In addition, the association between observed and simulated peak discharge across all four catchments is acceptable as indicated by the regression statistics in Table 4.5. Nonetheless, incidences of over and under simulations were evident and these could be attributed to similar reasons cited under verification of runoff volumes.

Similar to daily peak discharge, daily sediment yield was verified under sugarcane land cover conditions because there was no observed sediment yield data available under bare fallow conditions. Due to the fact that various sediment yield records were incomplete, only events documented by Maher (1990) together with a few consistent events were used in the verifications. The association between simulated and observed sediment yield events was reasonably good as shown by the regression statistics in Table 4.5.

Based on the results from this study, it is concluded that the *ACRU* model together with the parameter inputs from the SCDSS and Smithers *et al.* (1996), are suitable in the simulation of runoff volume, peak discharge and sediment yield from catchments under both bare fallow and sugarcane land cover and with various management practices in South Africa. Therefore, the *ACRU* model can be applied with confidence in the development of updated design norms for soil and water conservation structures in the sugar industry in South Africa.

4.6 Acknowledgements

South African Sugarcane Research Institute (SASRI) is greatly acknowledged for availing resources for this research. Appreciation is also extended to Prof JC Smithers and Mr SLC Thornton-Dibb for technical guidance on the setting up and application of the *ACRU* model.

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4.8 Appendix 4.1: *ACRU* Variables used in the Simulation of Runoff Volume

The various *ACRU* variables used in the simulation of runoff are shown in Table 4.6.

Table 4.6 Soil variable and parameter selections (after Smithers et al., 1996)

Variable/ Parameter*	Catchment 101	Catchment 102	Catchment 103	Catchment 104
DEPAHO	0.30	0.30	0.30	0.30
DEPBHO	0.43	0.49	0.49	0.49
WP1	0.228	0.248	0.248	0.192
WP2	0.239	0.244	0.245	0.220
FC1	0.344	0.367	0.368	0.304
FC2	0.370	0.375	0.376	0.347
PO1 (BF)	0.523	0.534	0.534	0.522
PO1 (SP)	0.505	0.523	0.523	0.493
PO2	0.455	0.475	0.475	0.433
ABRESP (BF)	0.70	0.70	0.70	0.70
ABRESP (SP)	0.25	0.25	0.25	0.22
BFRESP	0.21	0.25	0.25	0.22
COIAM (BF)	0.35	0.35	0.35	0.35
COIAM (SP)	0.40	0.25	0.20	0.25
SMDDEP (BF)	0.25	0.30	0.30	0.30
SMDDEP (SP)	0.35	0.35	0.35	0.35
COFRU	0.02	0.02	0.02	0.02
QFRESP	1.00	1.00	1.00	1.00

*Key:

(BF)	Bare fallow value of the variable/parameter
(SP)	Value of the variable/parameter during sugarcane production
DEPAHO, DEPBHO	Thicknesses of top- and subsoil respectively (m)
WP1, WP2	Permanent wilting points of top- and subsoil respectively ($m.m^{-1}$)
FC1, FC2	Drained upper limits of top- and subsoil respectively ($m.m^{-1}$)
PO1, PO2	Porosities of top- and subsoil horizons respectively ($m.m^{-1}$)

ABRESP	Saturated redistribution fraction from topsoil to subsoil
BFRESP	Saturated redistribution fraction from subsoil horizon to intermediate/groundwater store
COIAM	Coefficient of initial abstraction
SMDDEP	Effective depth of soil for stormflow response (m)
COFRU	Coefficient of base flow response
QFRESP	Catchment stormflow response fraction

4.9 Appendix 4.2: The MUSLE Parameters used in the Simulation of Sediment Yield

The various MUSLE parameters used in the simulation of sediment yield are shown in Table 4.7.

Table 4.7 MUSLE parameters used for the simulation of sediment yield

Input parameter/ variable**	Catchment 101	Catchment 102	Catchment 103	Catchment 104
SOIF1	0.31	0.20	0.20	0.43
SOIF2	0.24	0.14	0.14	0.34
ELFACT	4.53	4.06	2.68	3.72
PFACT	0.06	0.23	0.90	0.06
COVER (I) (bare fallow)*	1.00	1.00	1.00	1.00
SEDIST	1.00	1.00	1.00	1.00
ALPHA	8.934	8.934	8.934	8.934
BETA	0.56	0.56	0.56	0.56

* Tanyaş *et al.* (2015)

** Key:

SOIF1	Maximum soil erodibility factor
SOIF2	Minimum soil erodibility factor
ELFACT	Slope length and steepness factor
PFACT	Support practice factor
COVER (I)	Monthly cover factor
SEDIST	Catchment sediment yield response fraction
ALPHA and BETA	Location specific coefficients, default values calibrated for catchments in Texas, Oklahoma, Iowa and Nebraska in the USA used

4.10 Appendix 4.3: Sediment Yield Events used in Final Verification at the La Mercy Catchments under Sugarcane Land Cover

The sediment yield events used in final verification at the La Mercy catchments under sugarcane cover are shown in Table 4.8.

Table 4.8 Sediment yield events used in final verification at the La Mercy catchments under sugarcane cover

Catchment	Date	Observed runoff (mm)	Observed sediment yield ($t.ha^{-1}$)	Simulated sediment yield ($t.ha^{-1}$)
101	02/11/1985	1.3	0.72	0.53
	12/03/1986	2.4	0.02	0.01
	23/03/1987	3.1	0.05	0.01
	09/05/1988	0	0.00	0.00
	25/03/1991	27.2	0.05	0.02
	10/04/1995	6.6	0.06	0.25
	16/12/1995	0.2	0.00	0.00
102	02/11/1985	0	0.21	0.21
	12/03/1986	8.9	0.03	0.05
	23/03/1987	3.3	0.07	0.11
	09/05/1988	0	0.00	0.00
	25/03/1991	65.6	0.04	0.05
	10/04/1995	4.7	0.05	0.05
	16/12/1995	0.4	0.01	0.04
103	02/11/1985	0.6	0.72	0.61
	12/03/1986	5.4	0.08	0.10
	23/03/1987	1.8	0.05	0.08
	09/05/1988	0	0.00	0.00
	25/03/1991	47.2	0.02	0.14
	10/04/1995	7.7	0.00	0.09
	16/12/1995	0	0.00	0.00
104	12/03/1986	15.7	0.12	0.16

Catchment	Date	Observed runoff (mm)	Observed sediment yield (t.ha^{-1})	Simulated sediment yield (t.ha^{-1})
	23/03/1987	2.5	0.01	0.01
	09/05/1988	0	0.00	0.00
	25/03/1991	57.6	0.13	0.10
	10/04/1995	22.8	0.51	0.69
	22/12/1995	19	0.00	0.00
	27/12/1995	2.8	0.04	0.00

5 DEVELOPMENT AND ASSESSMENT OF AN UPDATED TOOL FOR THE DESIGN OF SOIL AND WATER CONSERVATION STRUCTURES IN THE SUGAR INDUSTRY OF SOUTH AFRICA

This Chapter is under review in *Agricultural Engineering International: CIGR Journal.*

Otim, D, Smithers, JC, Senzanje, A, van Antwerpen, R and Thornton-Dibb, SLC. "In press". Development and assessment of an updated tool for the design of soil and water conservation structures in the sugar industry of South Africa. *Agricultural Engineering International: CIGR Journal* "In press".

Abstract

Sugarcane in South Africa is frequently cultivated in diverse climatic and topographic conditions, and soils. These conditions pose high risks of erosion, and protection of cropped land in areas experiencing high rainfall has traditionally been provided by contour banks built across hillsides at low slopes. Platford (1987) developed a design nomograph for soil and water conservation structures in the sugar industry of South Africa using observations from runoff plots and the long term average annual soil loss simulated using the Universal Soil Loss Equation (USLE). However, soil erosion occurs on an event basis, and therefore the Modified Universal Soil Loss Equation (MUSLE) is best suited for simulation of event erosion. The MUSLE is embedded in the Agricultural Catchments Research Unit (*ACRU*) model and has been verified for catchments under sugarcane production in South Africa. The currently used sugar industry design nomograph was developed based on an unsustainable soil loss limit. This nomograph does not include impacts of regional variations of climate on soil erosion and runoff, nor explicitly account for large runoff events and their frequency of occurrence, vulnerability to soil erosion during break cropping, and the potential impact of climate change on runoff and soil loss. The objective of this study was to develop and assess an updated tool for the design of soil and water conservation structures in the sugar industry of South Africa. Emphasis was placed on developing an updated tool that was robust but simple to apply, based on sustainable soil loss limits, including regional variations of climate and their impacts on soil erosion and runoff, and including vulnerability during break cropping. The study area consists of sugarcane growing areas in South Africa, categorised into homogenous zones on the basis of growth cycle lengths as South Coast, North Coast, Zululand and Irrigated, and Midlands. The observed data consisted of daily rainfall for the period 1950 – 2017, maximum and minimum temperature, and A-pan data for the period 1950 – 1999. Based on expert opinion, representative daily weather stations were selected for each homogenous zone. With reference to practices in the sugar industry, scenarios were conceptualised and the *ACRU* model input variables and parameters were estimated for each scenario. Simulations with the *ACRU* model were conducted and the outcome used to build the Contour Spacing Design Tool (CoSDT) for the design of soil and water conservation structures in the sugar industry of South Africa, using MS Access as a background database and a graphical user interface. Examples of typical designs conducted using the CoSDT, and the sugar industry design nomograph and designs conducted by specialists in the sugar industry based on the SASRI nomograph are presented and assessed. Generally, differences existed between contour bank spacings designed using the CoSDT, and the current sugar industry design nomograph and the specialists' designs. The source of discrepancies was the fact that Platford (1987) developed the current sugar industry design nomograph using the USLE and assumed average values representing the entire sugar industry, while the CoSDT was developed using the MUSLE and parameters representative of each region in the sugar industry. Therefore, the CoSDT was found to be representative of conditions in the sugar industry of South Africa and recommended for use in place of the sugar industry design nomograph developed by Platford (1987). In conclusion, the CoSDT accounts for vulnerability of soils to erosion during break cropping by including the green manuring agronomic practice, while regional variations of climate and their impacts on soil erosion and runoff are addressed through using region specific climatic data in the simulations and subsequent development of the CoSDT. The robustness of the CoSDT is ensured by the over 46 080 scenarios contained in a database while its simplicity lies in the fact that practices are selected from drop down menus embedded in the MS Access graphical user interface.

Keywords: *ACRU*, design norm, soil and water conservation, soil loss, South Africa, sugarcane

5.1 Introduction

In South Africa, sugarcane is widely grown in diverse climatic and topographic conditions and on a range of soils, hence the soils are at high risk of erosion (Platford, 1987). For areas receiving high rainfall, protection of cropped land has traditionally been achieved through the use of contour banks built across a hillside at low slopes. However, sugarcane is not always grown on relatively gentle slopes for which this control system was designed. Various soil conservation practices exist and these include mechanical structures (*e.g.* contour bunds, terraces, check dams), soil management practices and agronomic measures (e.g. cover crops, tillage, mulching, vegetation strips, re-vegetation, and agroforestry) (Krois and Schulte, 2014). However, it is recommended that all approaches to soil conservation practices be employed to manage runoff and soil erosion from cultivated lands (Reinders *et al.*, 2016). Soil and water conservation structures (*e.g.* contour banks and spill-over roads) in the sugar industry of South Africa are currently designed using the nomograph developed by Platford (1987). The nomograph was developed using observations from runoff plots and the long term average annual soil loss estimated using the Universal Soil Loss Equation (USLE) (Wischmeier and Smith, 1965; Wischmeier and Smith, 1978). However, most of the erosion occurs during relatively few events, hence the need for event modelling (Schulze *et al.,* 2011). In addition, the USLE is limited scientifically in that the fundamental hydrologic and erosion processes are not represented explicitly and because of this, the USLE does not always simulate reasonable results of erosion (Renard *et al.*, 1991). The rainfall erosivity factor (*R*) is the driver of erosion processes in the USLE and yet rainfall erosivity is not uniformly distributed throughout the year. Therefore, since most of the erosion occurs during relatively few events, it is necessary to update the design norms with an event based model like the Modified Universal Soil Loss Equation (MUSLE) (Williams, 1975) which estimates individual sub-catchment sediment yield (Heritage *et al.*, 2004). In the MUSLE, the energy for sediment entrainment and transport is derived from the event peak discharge volume and peak flow rate (Lorentz *et al.*, 2012).The sugar industry design norms for spacing of contour banks recommends for specific designs for soil conservation structures whenever slopes are less than 3% or greater than 30% (Russell, 1994), although the sugar industry design nomograph includes slopes of up to 40% (Platford, 1987; SASA, 2002). There are also differences between the design norms contained in the National Soil Conservation Manual (van Staden and Smithen, 1989; DAWS, 1990), and design norms used in the sugar industry (Platford, 1987; SASA, 2002) (e.g. maximum slope and cover factors for sugarcane). The sugar industry design nomograph does not (Smithers, 2014):

(a) include any regional variations of climate and their impact on soil erosion and runoff,
(b) account for large runoff events and how frequently these occur,
(c) account for unplanned events (e.g. runaway fires) which do occur,
(d) include vulnerability during break cropping where the cover may be reduced, and

(e) include the potential impact of climate change on runoff and soil loss.

In addition to the above, Platford (1987) stated that an acceptable soil loss of 20 $t.ha^{-1}.year^{-1}$ was used in the development of the nomograph, which is not sustainable considering that tolerable soil losses in South Africa are estimated to be in the range 5 – 10 $t.ha^{-1}.year^{-1}$ (Matthee and Van Schalkwyk, 1984; Le Roux *et al.*, 2008). However, Platford (1987) noted that sustainable soil losses range from 4 to 12 $t.ha^{-1}.year^{-1}$ and that the impact on sustainability of soil loss from a deep soil profile is less than on a shallow soil profile. Furthermore, Platford (1987) employed subjective judgement in the development of the sugar industry design nomograph and some soil losses from the simulations used in building the nomograph were over 400 $t.ha^{-1}.year^{-1}$. The limits for the horizontal interval for soil and water conservation structures in the sugar industry nomograph range between 10 m and 140 m (Platford, 1987; SASA, 2002) while experts in the sugar industry use practical limits ranging between 10 m and 60 m (Wilkinson, 2019). The horizontal interval practical limits used by experts in the sugar industry are based on the South African Sugarcane Research Institute (SASRI) nomograph shown in Appendix 5.1 which was developed by SASRI in collaboration with the Department of Agriculture and Environmental Affairs (DAEA) (SASRI, 2019). On the other hand, the maximum horizontal interval for soil and water conservation structures in the nomograph for contour bank spacing found in the National Soil Conservation Manual is 60 m (van Staden and Smithen, 1989)**.** The objective of this paper was to develop an updated tool for the design of soil and water conservation structures in the sugar industry of South Africa. Emphasis was placed on developing an updated tool that was robust but simple to apply, based on sustainable soil loss limits, which include regional variations of climate and their impacts on soil erosion and runoff, and vulnerability during break cropping.

5.2 The MUSLE

The Modified Universal Soil Loss Equation (MUSLE), developed by Williams (1975), is an empirical equation that estimates the total soil yield for a storm event (Hui-Ming and Yang, 2009). The MUSLE was originally developed using data from eighteen small catchments located in Texas, Oklahoma, Iowa and Nebraska in the USA (Chen and Mackay, 2004) and it uses variables of runoff to drive the simulation of erosion and sediment yield (Williams and Arnold, 1997). In the MUSLE, the USLE rainfall erosivity factor (R) was replaced with a storm flow factor (Lorentz and Schulze, 1995). Erosive and transport energies are accounted for in the MUSLE through the inclusion of stormflow volume and peak discharge respectively (Williams and Berndt, 1977), both of which are projected to change in the future. Runoff from a catchment is influenced by interactions between rainfall intensity, antecedent soil moisture conditions and land cover (Smithers *et al.*, 1996), while peak discharge is dependent on catchment slope, runoff volume, rainfall depth, rainfall intensity and area of catchment (Schulze, 2011). Soils with large proportions of sand have large pores through which water drains freely and are at less risk of generating runoff while soils with high proportions of clay have tiny pores which inhibit drainage of water thereby increasing the risk of runoff (DEFRA, 2007). In addition, poorly drained soils tend to become wet and wet soils have greater risk of runoff. Soils with low clay content are less cohesive, more unstable and at greater risk of erosion (DEFRA, 2007). Generally, relationships between soil erosion and texture exist (D'Huyvetter, 1985) although different conclusions may be reached if variations in climate are taken into account (Manyevere *et al.*, 2016). The event sediment yield, Y_{sd} (t) is determined from stormflow volume for the event, Q_v (m^3), event peak discharge, q_p ($m^3.s^{-1}$), a soil erodibility factor, K ($t.h.N^{-1}ha^{-1}$), a slope length factor, L, slope steepness factor, S, cover management factor, C, supporting practices factor, P, and location specific MUSLE coefficients (α_{sy} and β_{sy}), as shown in Equation 5.1 (Hui-Ming and Yang, 2009). The location specific MUSLE coefficients were originally calibrated for catchments in Texas, Oklahoma, Iowa and Nebraska in the USA but have been adopted extensively with varying degrees of success (Williams, 1991). The limits for L and S factors were determined by Wischmeier and Smith (1978), adopted by Renard *et al.* (1991) in the Revised Universal Soil Loss Equation (RUSLE) and subsequently adopted by Lorentz and Schulze (1995) for use in the MUSLE whenever detailed field information is available. The limits for L and S factors are shown in Appendix 5.2.

$$Y_{sd} = \alpha_{sy} (Q_v . q_p)^{\beta_{sy}} K.LS.C.P \qquad (5.1)$$

Stormflow depth in the Agricultural Catchments Research Unit (*ACRU*) model is estimated using a modified SCS procedure shown in Equation 5.2 (Schmidt *et al.*, 1987; Schulze, 1995c), while the equation for estimating peak discharge employs the SCS triangular-shaped unit hydrograph approach which is shown in Equation 5.3 (Schulze and Schmidt, 1995; Schulze *et al.*, 2004).

$$Q_s = \frac{(P_g - I_a)^2}{(P_g - I_a + S)} \quad for \quad P_g > I_a \qquad (5.2)$$

where

Q_s = stormflow depth (mm),

P_g = gross daily precipitation amount (mm),

I_a = initial abstraction prior to stormflow commencement (mm), and

S = potential maximum soil water retention (mm).

$$\Delta q_p = \frac{0.2083 A \Delta Q}{\frac{\Delta D}{2} + L} \tag{5.3}$$

where

Δq_p = peak discharge of incremental unit hydrograph ($m^3.s^{-1}$),

ΔQ = incremental storm flow depth (mm),

A = catchment area (km^2),

L = catchment lag time (h), and

ΔD = incremental time duration (h).

The catchment lag time, L (h) is determined from catchment area, A (km^2), 2-year return period 30-minute rainfall intensity, i_{30} ($mm.h^{-1}$), mean annual precipitation, *MAP* (mm), and average catchment slope, S (%), as shown in Equation 5.4 (Schmidt and Schulze, 1984).

$$L = \frac{A^{0.35} MAP^{1.1}}{41.67 S^{0.3} i_{30}^{0.87}} \tag{5.4}$$

The MUSLE is embedded in the *ACRU* model which is a daily time step, physical-based conceptual agrohydrological model (Schulze, 1975; Schulze *et al.*, 1995; Smithers and Schulze, 1995; Smithers *et al.*, 1996). Verification of the *ACRU* model was conducted for catchments under sugarcane production and presented in Chapter 4 and, from the results, it was concluded that the *ACRU* model may be applied with reasonable confidence in the simulation of runoff volume, peak discharge and sediment yield from catchments under both bare fallow and sugarcane land cover and with various management practices in South Africa.

Gwapedza *et al.* (2018) conducted a sensitivity analysis of MUSLE input parameters on sediment yield simulations and the results showed that the MUSLE was most sensitive to vegetation cover (*C*) followed by soil erodibility (*K*), topographic factors (*LS*) and practice factors (*P*). Variation of the MUSLE input parameters between minimum and maximum limits resulted in soil loss increases of 17 567%, 2 317%, 940% and 900% for *C*, *K*, *LS* and *P* factors respectively. According to Tanyaş *et al.* (2015), the *C* factor is of significant importance because it is the most influential factor on erosion. Hence, the need for a more realistic estimate of the *C* factor which varies gradually as nature itself. Alexandridis *et al.* (2015) demonstrated that there is a significant difference in the estimation of erosion with the USLE when using variable time steps for the *C* factor. Therefore, consideration of temporal and spatial variation of the *C* factor is of high importance.

5.3 Data and Methods

A description of the data and methods employed in this study are provided below.

5.3.1 Study area

The study area consists of sugarcane growing areas in South Africa, predominantly in KwaZulu-Natal (KZN) and to a less extent in Mpumalanga provinces (SASA, 2016; SASA, 2018b), as indicated in Figure 5.1.

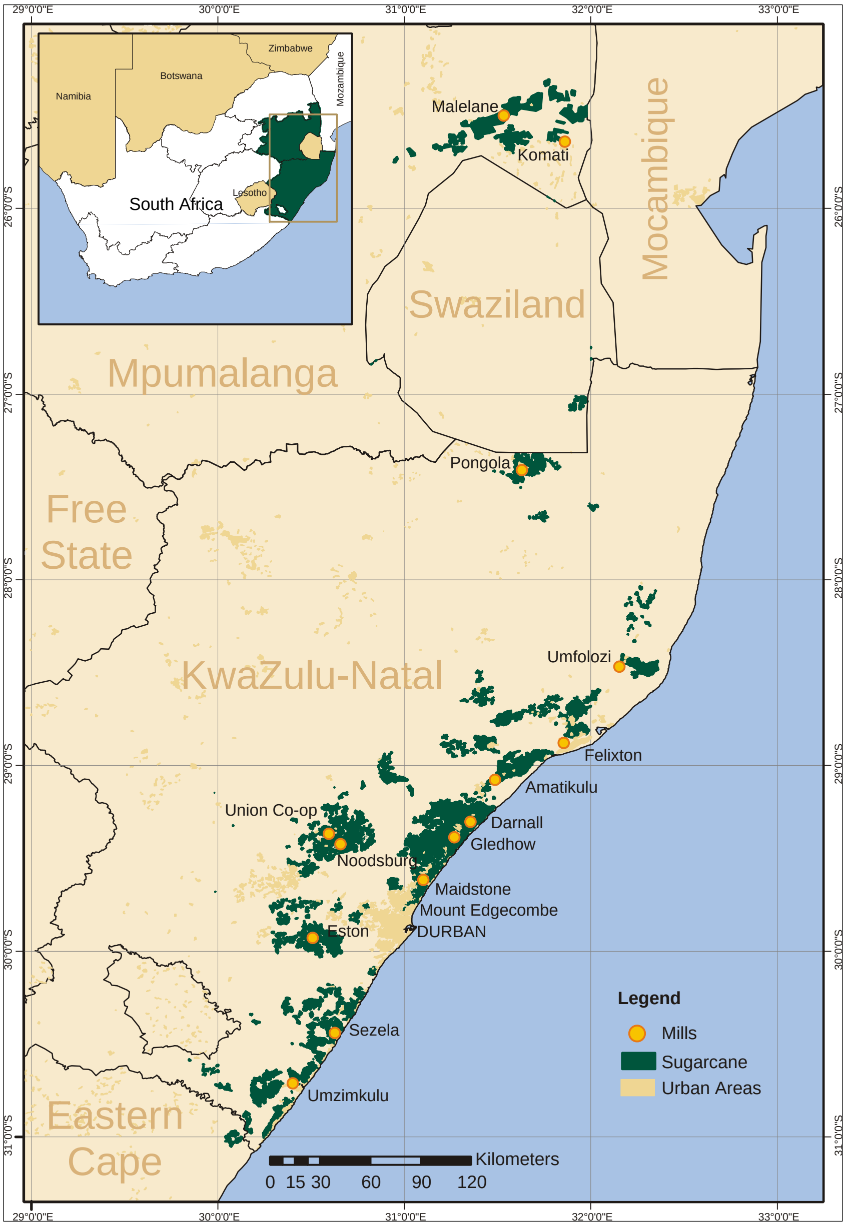

Figure 5.1 Location of sugarcane production areas and mills in South Africa (SASA, 2018b)

These regions receive Mean Annual Precipitation (MAP) ranging from 300 mm to more than 1 100 mm, with annual minimum temperatures ranging between 12.5° C and 19.5° C while annual maximum temperatures range between 21° C and 33° C (SASA, 2018a). The harvest-to-harvest cycles (ratoon lengths) are mainly influenced by temperature conditions and vary from 12 to 21 months, as shown in Figure 5.2 (Schulze, 2013). For dryland sugarcane, ratoon lengths range from 12 months along the northern KwaZulu-Natal coastline and parts of Mpumalanga to 20 to 22 months in inland growing areas where lower temperatures and hence heat units prevail (Schulze and Kunz, 2010).

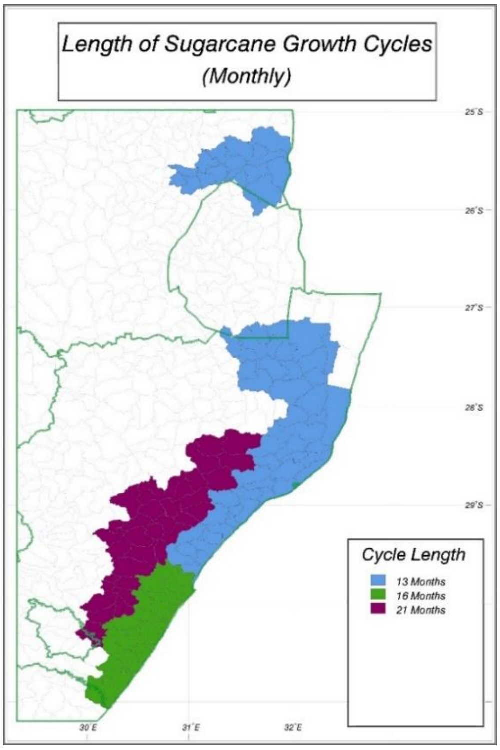

Figure 5.2 Regions with different sugarcane growth cycle lengths in South Africa (Schulze, 2013)

The sugarcane cultivation areas are further classified into relatively homogenous climatic zones as South Coast, North Coast, Zululand and Irrigated, and Midlands on the basis of growth cycle lengths (Schulze, 2013) as shown in Figure 5.3. The ratoon lengths for South Coast, North Coast, Zululand and Irrigated, and the Midlands are 16, 13, 12 and 21 months respectively while the respective Mean Annual Precipitations (MAPs) are 934, 1 146, 642 and 818 mm, respectively. In addition, sugarcane replant cycles after the last ratoon crop are 10, 10, 7 and 16 years for the South Coast, North Coast, Zululand and Irrigated, and the Midlands respectively. The sugarcane cultivation areas lie between latitudes of 25° S and 31° S and between longitudes of 30° E and 32° E (SASRI, 2011), while the altitude ranges between 0 m and 1 143 m (Palmer and Ainslie, 2006). Land slopes range between 0% and 40% with 61% of the area having land slopes between 0% and 10%, 24% of the area having land slopes in the range 11 to 20%, and 14% of the area having land slopes in the range 21 to 40% (Mthembu *et al.*, 2011). The sugarcane growing areas consist of 49 soil forms and 154 soil series which are divided into five main groups according to colour and six textural classes (MacVicar *et al.*, 1977; Smithers *et al.*, 1995; Botha *et al.*, 1999). The six textural classes are clay, loamy sand, sand, sandy clay, sandy clay loam and sandy loam.

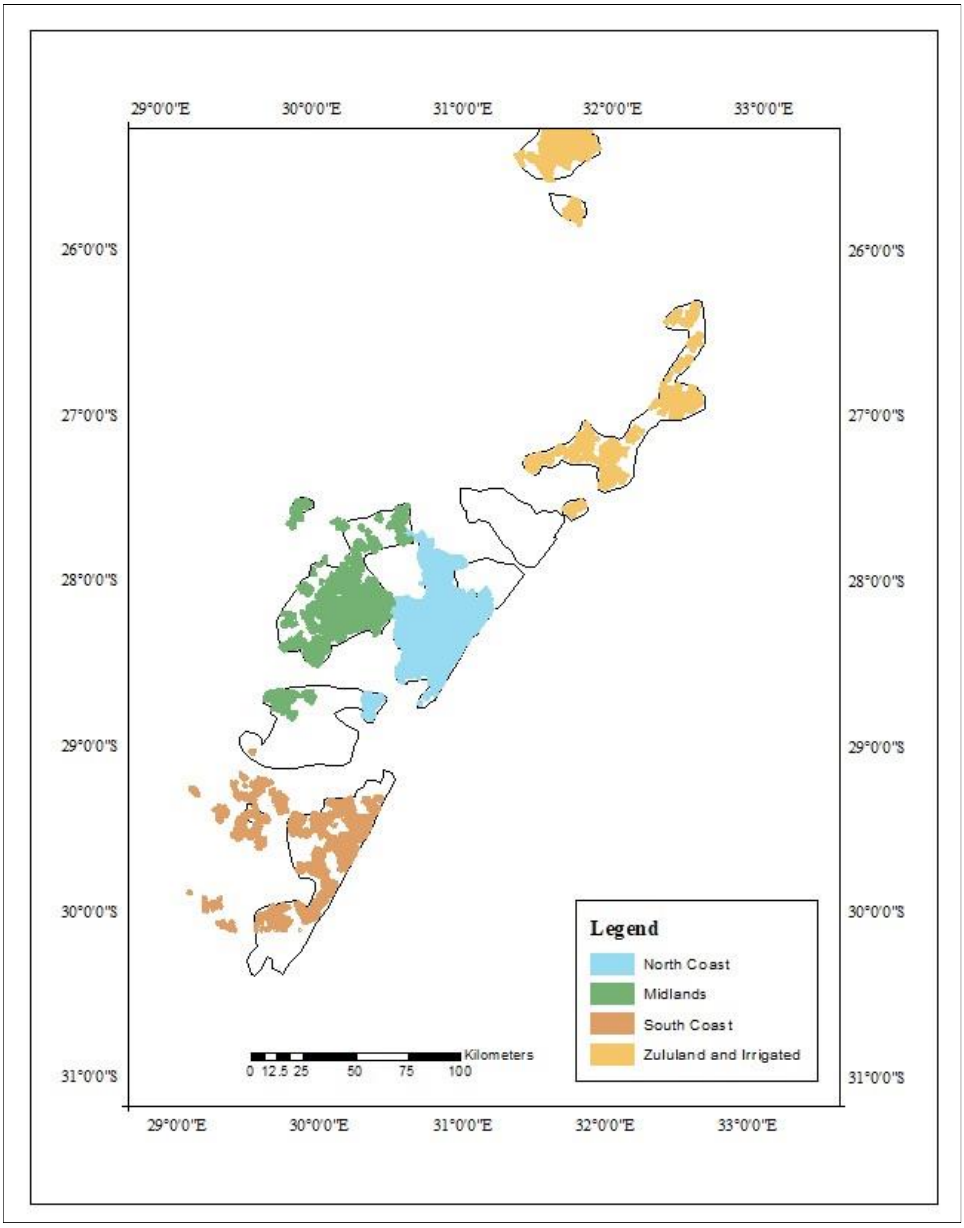

Figure 5.3 Relatively homogenous climatic zones in the sugar industry of South Africa (Mthembu *et al.*, 2011)

5.3.2 Methodology

In this section, the steps taken to develop an updated tool for the design of soil and water conservation structures in the sugar industry of South Africa are described.

5.3.2.1 Data

Daily observed rainfall consisting the total rainfall received on a given day, maximum and minimum temperature and A-pan evaporation data were obtained from the SASRI. The data comprises daily observed rainfall for the period 1950 – 2017, daily maximum and minimum temperature, and A-pan data for the period 1950 – 1999. In addition, Land Use Plans (LUPs) containing designs of soil and water conservation structures prepared by specialists in the sugar industry, *i.e.* Naude and Makhaye (2018) and Wilkinson and Gumede (2018) who used the SASRI design nomograph shown in Appendix 5.1 for spacing of contour banks, were obtained from SASRI and Noodsberg Cane Growers Association (NCGA). The LUPs were obtained for each region in the sugar industry.

5.3.2.2 Identification of relatively homogeneous regions

Considering that sugarcane land cover has the greatest influence on simulated sediment yield (Gwapedza *et al.*, 2018), the sugarcane growing areas were clustered into relatively homogenous climatic zones based on the growth cycle lengths of sugarcane which are mainly influenced by temperature conditions. The zones are South Coast, North Coast, Zululand and Irrigated, and Midlands.

5.3.2.3 Selection of daily weather stations

Expert opinion (Schulze and Davis, 2018) was sought in the selection of representative weather stations for each of the sugarcane homogenous zones. The driver stations used in the generation of quinary catchments within the sugar industry were selected as representative stations and they are summarised in Table 5.1. A quinary catchment is a topographically defined basin, or watershed area, which collects water and drains it at an exit (Schulze, 2011). It is the most detailed spatial level of operational catchment for general planning purposes in South Africa.

Table 5.1 Representative weather stations for the sugarcane growing regions (Schulze and Davis, 2018)

Region	Station Name	SASRI Station No.	Quinary Catchment No.	Longitude	Latitude	Mean Annual Rainfall (mm)
South Coast	Hibberdene	106	4805	30^{o} 30' E	30^{o} 30' S	934
Midlands	Seven Oaks	22	4729	30^{o} 36' E	29^{o} 14' S	818
North Coast	Felixton	144	5111	31^{o} 53' E	28^{o} 50' S	1 146
Far North and Irrigated	Mkuze	154	5223	32^{o} 01' E	27^{o} 36' S	642

5.3.2.4 Selection and parameterisation of soils

Six soil textural classes namely clay, loamy sand, sand, sandy clay, sandy clay loam and sandy loam were extracted from the 154 soil series of the sugar industry with varying clay distribution models. Due to the variations of water holding capacities in the soil textural classes and in order to determine representative water holding capacities for each textural class, weighted averages of water holding capacities across the textural classes were calculated and the results compared with opinions from soil science experts in the sugar industry. Weighting of water holding capacities was based on the number of clay distribution models in each textural class. The weighted water holding capacities for the six textural classes were found to be representative of soils in the sugar industry (van Antwerpen, 2019) and they are summarised in Table 5.11 in Appendix 5.3.

The soil *K* factors were estimated using both Level 1 and Level 3 options documented by Lorentz and Schulze (1995) and the results compared with expert opinions from the sugar industry. Level 1 option determines the soil erodibility class from the Binomial Soil Classification (MacVicar *et al.*, 1977) of the soil, while Level 3 option determines soil erodibility based on more complete soil physical data. From the expert opinion (van Antwerpen, 2019), *K* factors estimated from the Level 1 were found to be representative of the soil erodibilities in the sugar industry. The *K* factors for the six textural classes are shown in Table 5.12 in Appendix 5.3.

5.3.2.5 Simulation scenarios and parameterisation

Scenarios used in the generation of the updated design norms were conceptualised based on practices in the sugar industry identified from SASRI (2016) and consultations with stakeholders in the industry. In so doing, omitted practices in the sugar industry design nomograph were addressed. For example, vulnerability during break cropping was accounted for by including green manuring agronomic practices as an option while regional variations of climate and their impacts on soil erosion and runoff were addressed through clustering the sugarcane growing areas into homogenous climatic zones. The variables and practices considered in the simulations are summarised in Table 5.2 which resulted in 46 080 scenarios simulated. *ACRU* parameters were estimated for each scenario based on verifications conducted in Chapter 4 and the parameter values are presented in Appendix 5.3.

Table 5.2 Simulation scenarios used in the updated design norms for soil and water conservation structures

Variable	Simulation Scenario
Region	South Coast, North Coast, Zululand and Irrigated, and Midlands
Soil Texture	Clay, Loamy sand, Sand, Sandy clay, Sandy clay loam and Sandy loam
Slope	0 – 40%
Structure	No structures, Water Carrying Terrace and Spillover Road
Tillage Type	Minimum Tillage and Conventional Tillage
Agronomic Practice	Green Manuring (soy bean and oats) and No Green Manuring (bare fallow)
Harvesting Method	Burnt and tops scattered, Burnt and reburnt (no surface residue), Mulched, and Mulched with strip or panel harvesting (*i.e.* harvesting conducted at end of each ratoon length and *C* factors varied over ratoon length)

5.3.2.6 Development of an updated tool for the design of soil and water conservation structures and checking the adequacy of existing designs in the sugar industry of South Africa

Different combinations of scenarios shown in Table 5.2 were simulated for the period 1950 – 2017 using daily rainfall for the period 1950 – 2017 and average maximum and minimum temperatures and average evaporation for the period 1950 – 1999, and for a hypothetical 1 km^2 catchment using the MUSLE embedded in the *ACRU* model, with the *L* and *S* factors maintained within theoretical limits proposed by Wischmeier and Smith (1978) (*i.e.* horizontal interval limits ranging from 6 m to 305 m) and *L* varied to limit soil losses to less than a maximum tolerable limit of 5 $t.ha^{-1}.year^{-1}$ (Matthee and Van Schalkwyk, 1984; Le Roux *et al.*, 2008). The soil losses were obtained by accumulating simulated individual sediment yield events on an annual basis and averaged for the entire period (*i.e.* 68 years). The *ACRU* model is a catchment model and rather than apply it to simulate catchments of varying areas, a hypothetical 1 km^2 catchment was selected to act as representative catchment. However, any area selected would not give different simulated responses and other studies in South Africa have utilised the hypothetical 1 km^2 catchment (Lumsden *et al.*, 2003; Smithers *et al.*, 2018). Daily maximum and minimum temperatures and average evaporation for the period 2000 – 2017 were not available from the weather stations, hence, the average values were used in the simulations.

Furthermore, simulations with *L* factors maintained within practical limits used by van Staden and Smithen (1989) in the National Soil Conservation Manual and the SASRI nomograph (*i.e.* horizontal intervals ranging from 10 m to 60 m) were conducted in order to align the practical limits with the National Soil Conservation Manual. The different scenario combinations were then used to build the updated tool, hereafter termed Contour Spacing Design Tool (CoSDT), for the design of soil and water conservation structures and checking the adequacy of existing designs in the sugar industry of South Africa. CoSDT was built using MS Access as a database and a graphical user interface. The MS Access graphical user interfaces for the design of soil and water conservation structures and checking the adequacy of existing designs are shown in Figure 5.4 and Figure 5.5 respectively. The MS Access graphical user interface coupled with a database containing over 46 080 scenarios ensured the CoSDT was robust but simple to apply.

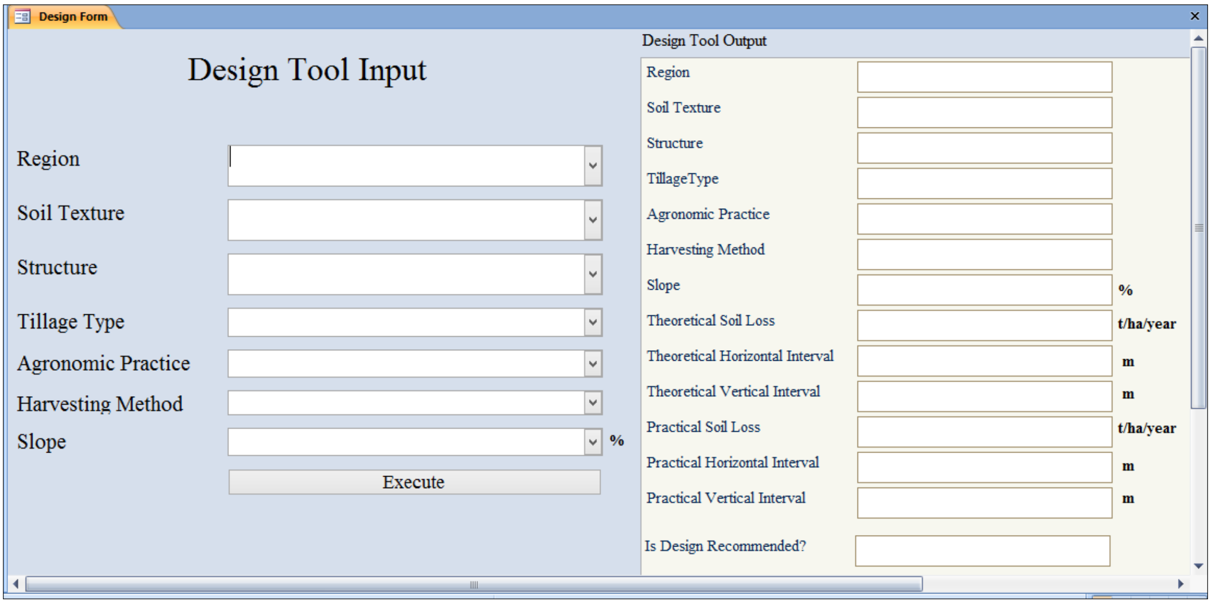

Figure 5.4 MS Access graphical user interface for the design of soil and water conservation structures in the sugar industry of South Africa

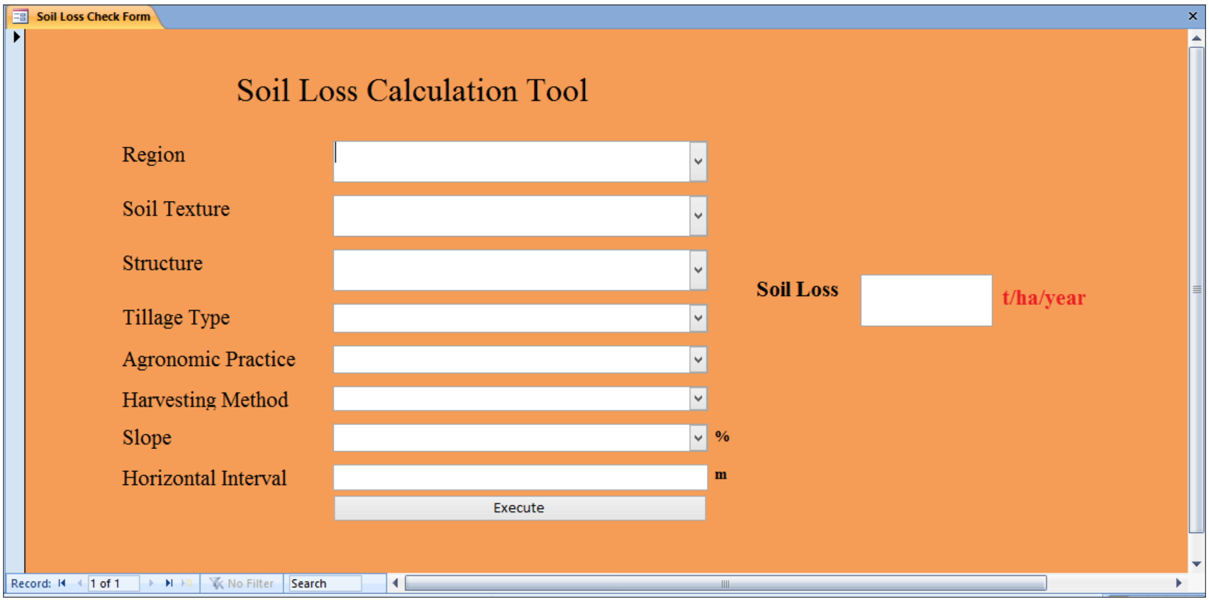

Figure 5.5 MS Access graphical user interface for checking the adequacy of existing designs in the sugar industry of South Africa

5.3.2.7 Analysis of relationships in accumulated annual rainfall and runoff across different relatively homogenous climatic zones

Plots (*i.e.* graphs) of simulated accumulated rainfall and runoff over time across the different relatively homogenous climatic zones were undertaken and analysed to determine how rainfall and runoff varies across each region. The assessment involved comparison of magnitudes of rainfall and runoff over the period in each region.

5.3.2.8 Analysis of regional variations of climate on sediment yield

Plots (*i.e.* graphs) of accumulated simulated sediment yield over time across the different homogenous climatic zones were made and analysed to determine how soil loss varies across each region. The assessment involved comparison of the magnitudes of sediment yield over the period and related to rainfall received and the ratoon lengths in each region.

5.3.2.9 Analysis of variation of sediment yield across different soil types

In order to analyse the variation of soil erosion across different soil types, plots of accumulated sediment yield against time for each soil type were made on the same graph. A select scenario for a single region (*i.e.* North Coast) was used as relationships are similar irrespective of region and scenario and analysis involved comparison of magnitudes of accumulated sediment yield over the period across the different soil types.

5.3.2.10 Comparison of designs from the CoSDT and the current sugar industry design nomograph for spacing of contour banks

The spacing of soil and water conservation structures for a typical scenario was designed using the CoSDT and compared against designs from the current sugar industry design nomograph for spacing of contour banks. In addition, designs from the CoSDT were compared against designs from LUPs prepared by Naude and Makhaye (2018) and Wilkinson and Gumede (2018), who are specialists in the sugar industry, using the SASRI nomograph. For equitable comparisons, the limits of horizontal intervals range in the current sugar industry design nomograph which are from 10 m to 140 m were retained in the CoSDT for the comparisons. Similarly, the horizontal interval limits in the current National Soil Conservation and SASRI design nomographs which range from 10 m to 60 m were retained in the CoSDT in the comparisons with designs from LUPs prepared by specialists in the sugar industry. Furthermore, soil loss estimates from the sugar industry design nomogrpah and the SASRI nomograph used by specialists in the sugar industry were calculated with the USLE and the various parameters presented by Platford (1987). Use of the CoSDT for design involves selection of typical scenario from dropdown lists under the "Design Tool Input". The results for horizontal interval, vertical interval and soil loss are then returned in the "Design Tool Output" section. In order to check the adequacy of a given design and practice, the graphical user interface shown in Figure 5.5 is used and requires input of the horizontal interval to be entered before execution and returns the expected soil loss from the selected design and practice. Steps taken to conduct and check designs with the sugar industry design nomograph for spacing of contour banks are presented by Platford (1987).

5.4 Results and Discussion

The results and discussions of the simulations used in the development and assessment of the CoSDT for the design of soil and water conservation structures in the sugar industry of South Africa are presented in this section. It is important to note that 46 080 different scenarios were simulated and only a few scenarios have been selected for discussion. However, the relative relationships exhibited are similar irrespective of the scenario and the only differences are in the magnitudes of runoff and sediment yield. In addition, analysis of relationships presented in Sections 5.4.1 to 5.4.3 was conducted using the "No Structures" scenario to eliminate effects of soil and water conservation structures on runoff and sediment yield.

5.4.1 Relationships in accumulated annual rainfall and runoff across different homogenous climatic zones

Plots (*i.e.* graphs) of accumulated annual rainfall for the four relatively homogenous climatic zones in the sugar industry of South Africa are shown in Figure 5.6 whereas plots of accumulated annual runoff simulated for the four homogenous climatic zones in the sugar industry of South Africa for a select scenario are shown in Figure 5.7.

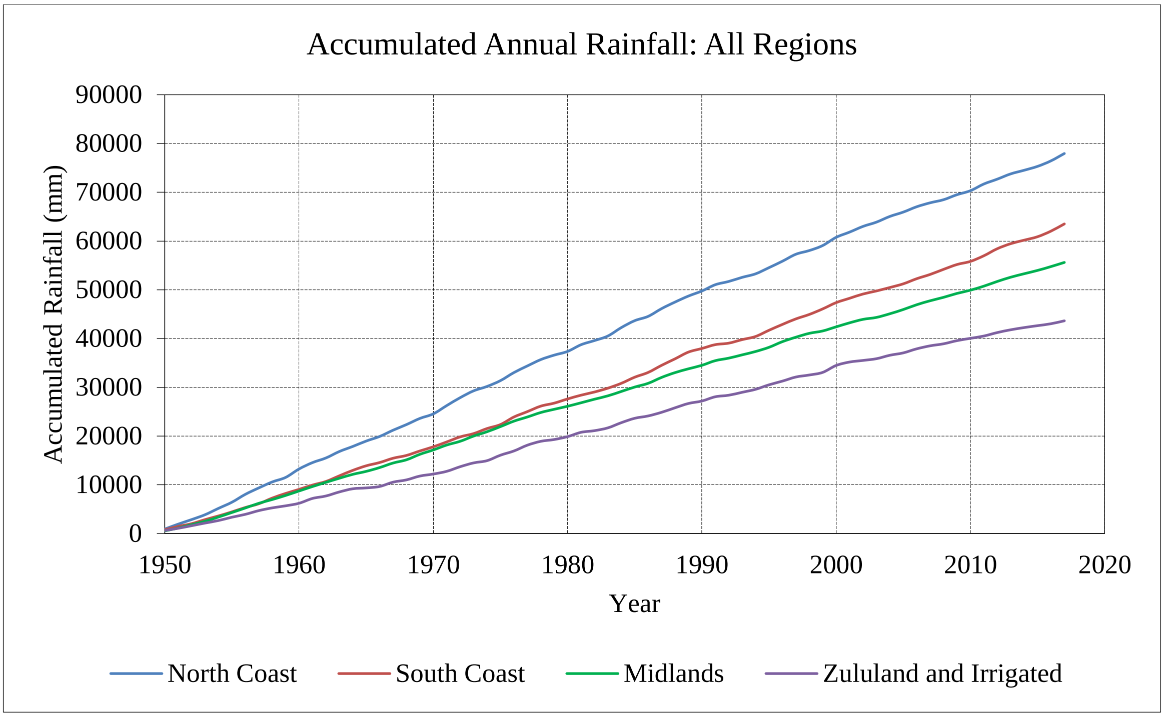

Figure 5.6 Relationships in accumulated annual rainfall from sugarcane fields across the different relatively homogenous climatic zones

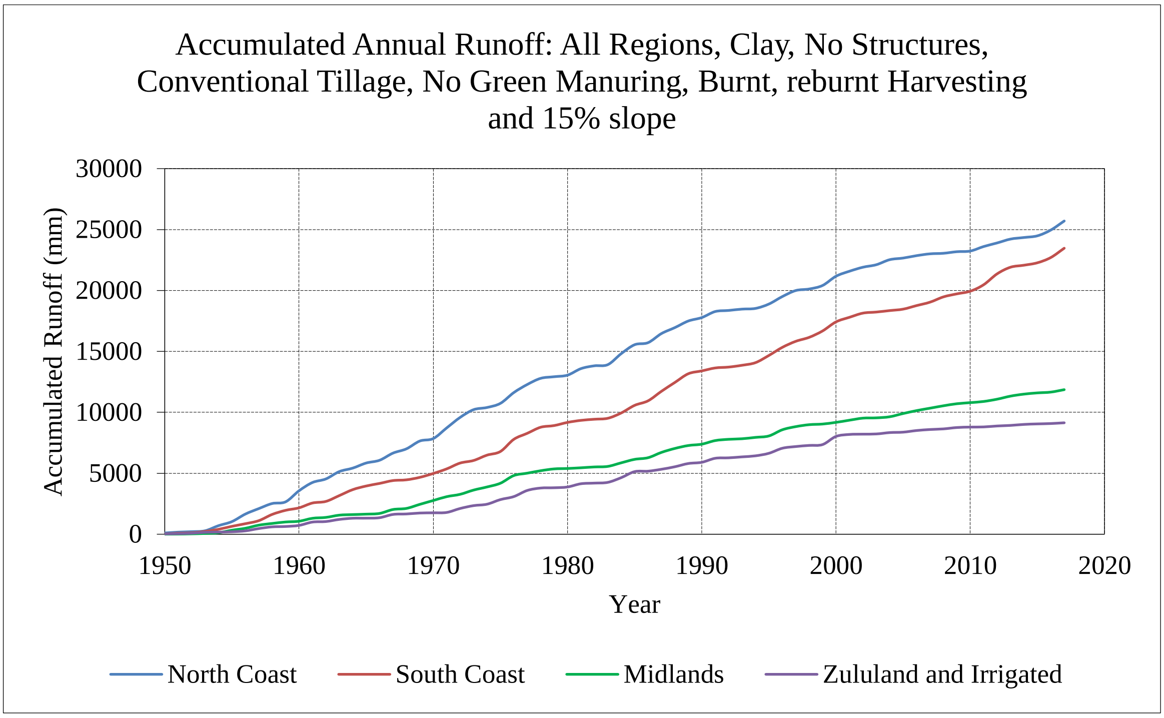

Figure 5.7 Relationships in accumulated annual runoff from sugarcane fields across the different relatively homogenous climatic zones

From Figure 5.6, it is evident that the largest accumulated annual rainfall occurs in the North Coast followed by the South Coast, Midlands, and Zululand and Irrigated regions. The relationship exhibited is attributed to the variations in rainfall in the relatively homogenous climatic zones. Similarly in Figure 5.7, it is evident that the largest accumulated annual runoff occurs in the North Coast followed by the South Coast, Midlands, and Zululand and Irrigated regions. The relationship exhibited is logical and attributed to the variations in rainfall in the relatively homogenous climatic zones as shown in Figure 5.6. Rainfall, which is the driver of runoff, is the highest in the North Coast followed by the South Coast, Midlands, and Zululand and Irrigated regions.

5.4.2 Impact of regional variations of climate on sediment yield

Plots (*i.e.* graphs) of accumulated annual sediment yield simulated for the four homogenous climatic zones in the sugar industry of South Africa for a select scenario are shown in Figure 5.8.

Generally, the largest accumulated annual sediment yield occurs in the South Coast followed by North Coast, Zululand and Irrigated and Midlands regions, as shown in Figure 5.8 for a specific scenario. The relationship exhibited is reasonable and attributed to the variations in rainfall intensities and ratoon lengths in the homogenous climatic zones. The 30 minute, 2 year rainfall intensity estimated from maps of rainfall distribution zones and used in the computation of peak discharge which is a driver of sediment yield, for South Coast, North Coast, Zululand and Irrigated and the Midlands are 60, 53, 50 and 68 $mm.h^{-1}$ respectively, while the ratoon lengths which influence sugarcane cover and hence sediment yield are 16, 13, 12 and 21 months respectively. The lowest sediment yield was simulated in the Midlands and it is attributed to the longest ratoon length which provides more vegetation cover to protect the soils against erosion compared to the other regions, even though it receives the most intense rainfall. On the other hand, the relationship exhibited at the South Coast, North Coast, and Zululand and Irrigated regions which have closely related ratoon lengths is attributed to the variations in rainfall intensities and runoff depths shown in Figure 5.7.

Further comparisons of accumulated annual sediment yield shows that the largest simulated sediment yield varied across regions depending on prevailing circumstances. This is attributed to differences in ratoon lengths across regions and differences in harvesting periods all of which affect sugarcane cover factors and hence erosion and the temporal distribution of rainfall at the sites used to represent the regions.

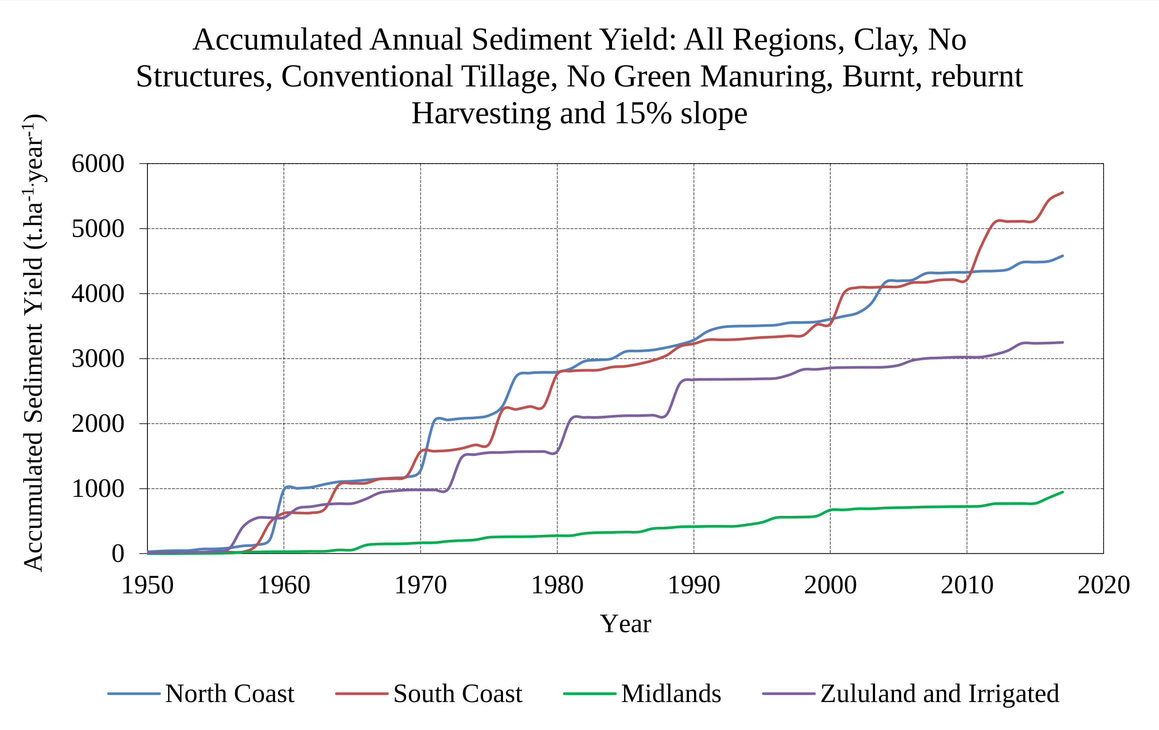

Figure 5.8 Relationships in accumulated annual sediment yield from sugarcane fields across the different homogenous climatic zones

5.4.3 Impact of soil texture on sediment yield

Plots (*i.e.* graphs) depicting relationships in accumulated annual sediment yield from different soil textures in the North Coast region and the Midlands for a specific scenario are shown in Figure 5.9 and Figure 5.10 respectively, while a discussion of the relationships is presented thereafter.

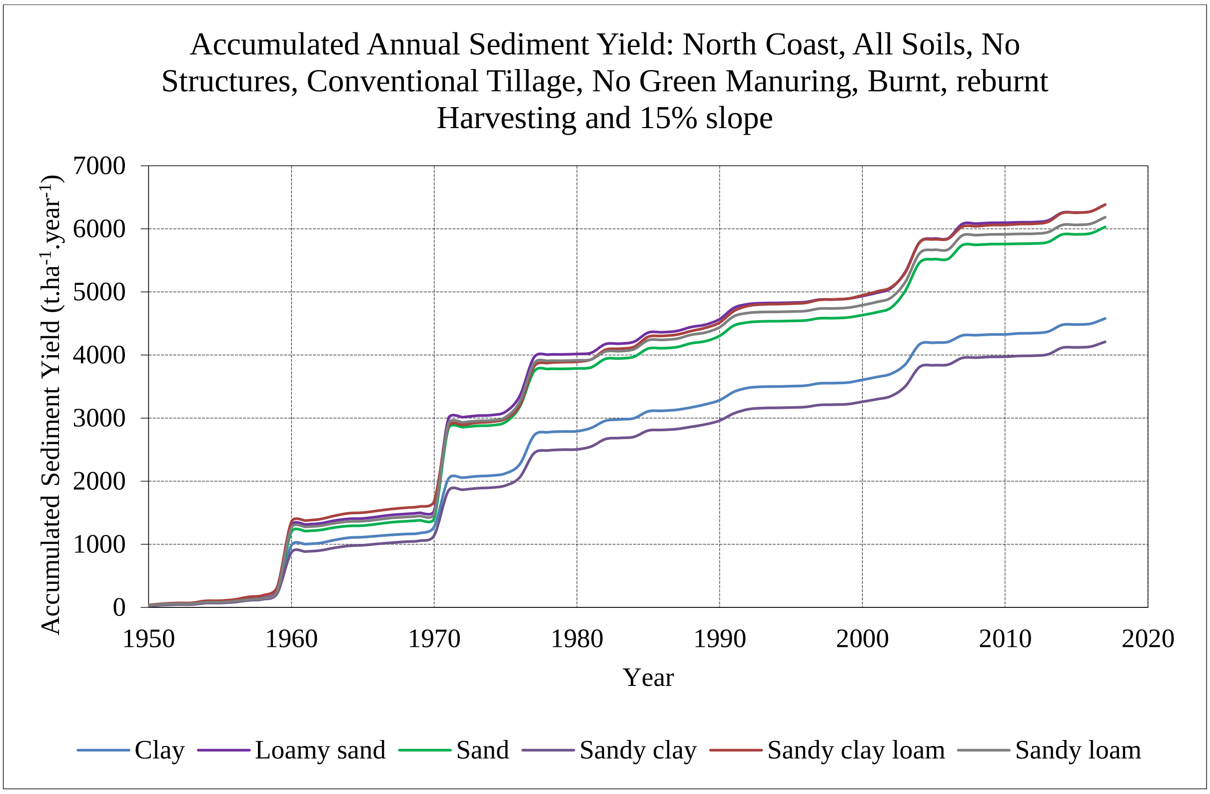

Figure 5.9 Relationships in accumulated annual sediment yield from different soils in the North Coast region

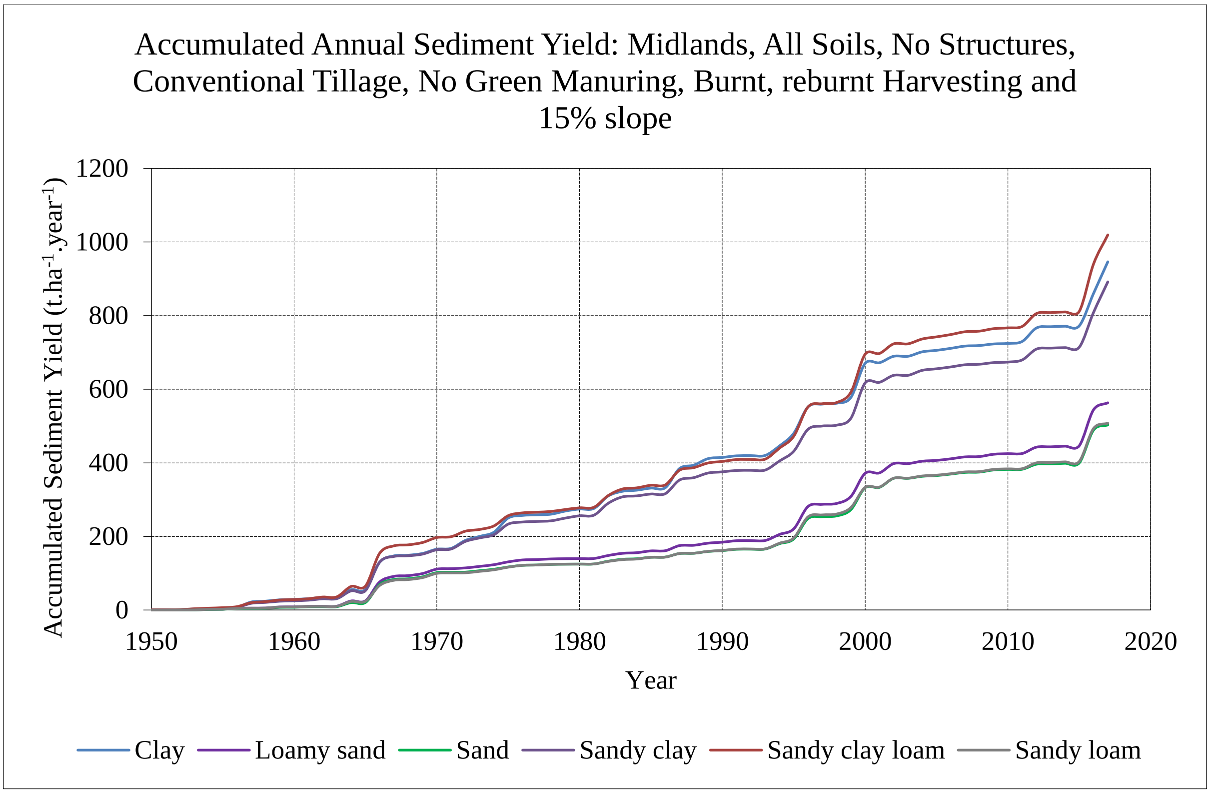

Figure 5.10 Relationships in accumulated annual sediment yield from different soils in the Midlands region

From Figure 5.9, it is evident that loamy sand soil is the most susceptible to erosion followed by sandy clay loam, sandy loam, sand, clay and sandy clay in the North Coast. This relationship is also exhibited by soils in the South Coast and Zululand and Irrigated regions. The relationships are logical and they are attributed to the physical properties of the soils which influence soil erosion. Sandier soils are less cohesive than clayey soils and hence more unstable and at greater risk of erosion.

On the other hand, the erodibility relationship exhibited in the Midlands region is different from that at the North Coast and other regions discussed earlier, as shown in Figure 5.10. Four rainfall distribution zones exist in South Africa (*i.e.* 1, 2, 3 and 4) with zone 1 receiving the least intense rainfall (Type 1 rainfall intensity distribution) and zone 4 (Type 4 rainfall intensity distribution) receiving the most intense rainfall. Initially, it was suspected that the rainfall of higher intensity received in the Midlands region compared to the North Coast, South Coast, and Zululand and Irrigated regions was responsible for the difference in relationships. From Figure 5.10, it is evident that the clayey soils are more susceptible to erosion than the sandier soils with sandy clay loam being the most susceptible followed by clay, sandy clay, loamy sand, sandy loam and sand. Clayey soils have lower infiltration rates than sandier soils, and considering that the Midlands region receives high intensity rainfall, the clayey soils drain very slowly thereby increasing the risk of runoff which further increases the amount of sediment yield generated (*i.e.* detached and transported). In order to investigate the effect of rainfall intensity further, the rainfall distribution of the Midlands (Type 3) was changed to Type 2 rainfall distribution of lesser intensity in the *ACRU* model and simulations conducted. However, there was no difference in relationships exhibited with more sediment yield simulated from clayey soils than sandier soils. However, when the Midlands simulations were conducted with rainfall from other regions and the other parameters unchanged, the sediment yield generated from clayey soils was less than sediment yield from sandier soils. An inspection of the daily rainfall from the four regions showed that daily rainfall from the Midlands was low compared to other regions and the Midlands had more rain days than the other regions. In addition, the frequency of occurrence of low rainfall depths (*i.e.* $\leq$ 10 mm) is higher in the Midlands than the other regions, whereas the frequency of occurrence rainfall depths greater than 10 mm is lower in the Midlands than the other regions as shown in Figure 5.11. According to Manyevere *et al.* (2016), relationships between soil erosion and texture may vary with variations in climate. Therefore, it is postulated that the relationship exhibited in the Midlands is attributed to the relatively low daily rainfall occurring more frequently compared to the North Coast, South Coast, and Zululand and

Irrigated regions. This is because, the frequently occurring low rainfall makes the soils wet and with clayey soils having poorer drainage than sandier soils, more runoff is generated from the clayey soils thus increasing the risk of sediment yield as shown in Figure 5.12 where, peak discharge is greater in clayey soils than sandier soils.

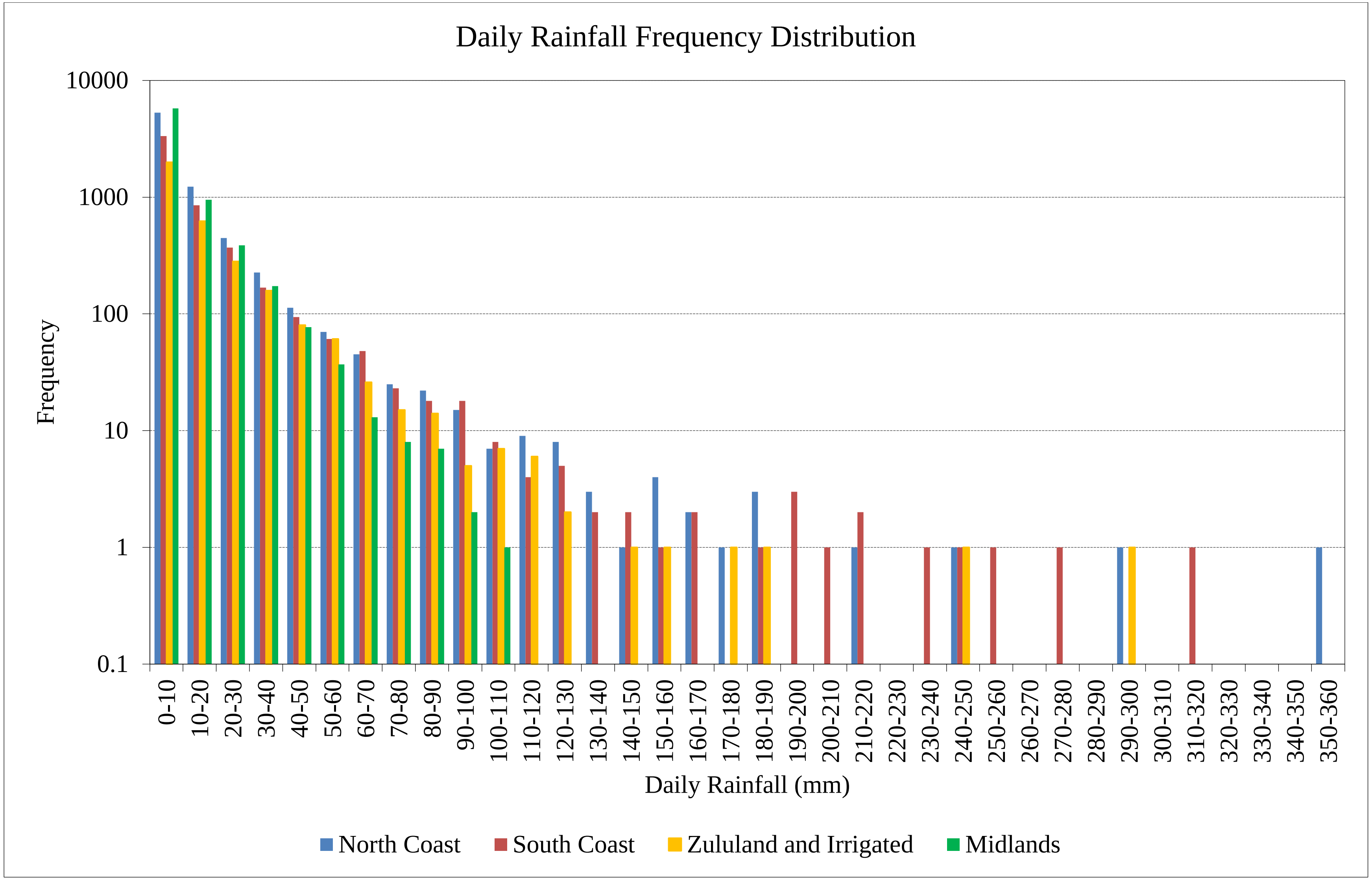

Figure 5.11 Frequency distribution of daily rainfall in the four regions

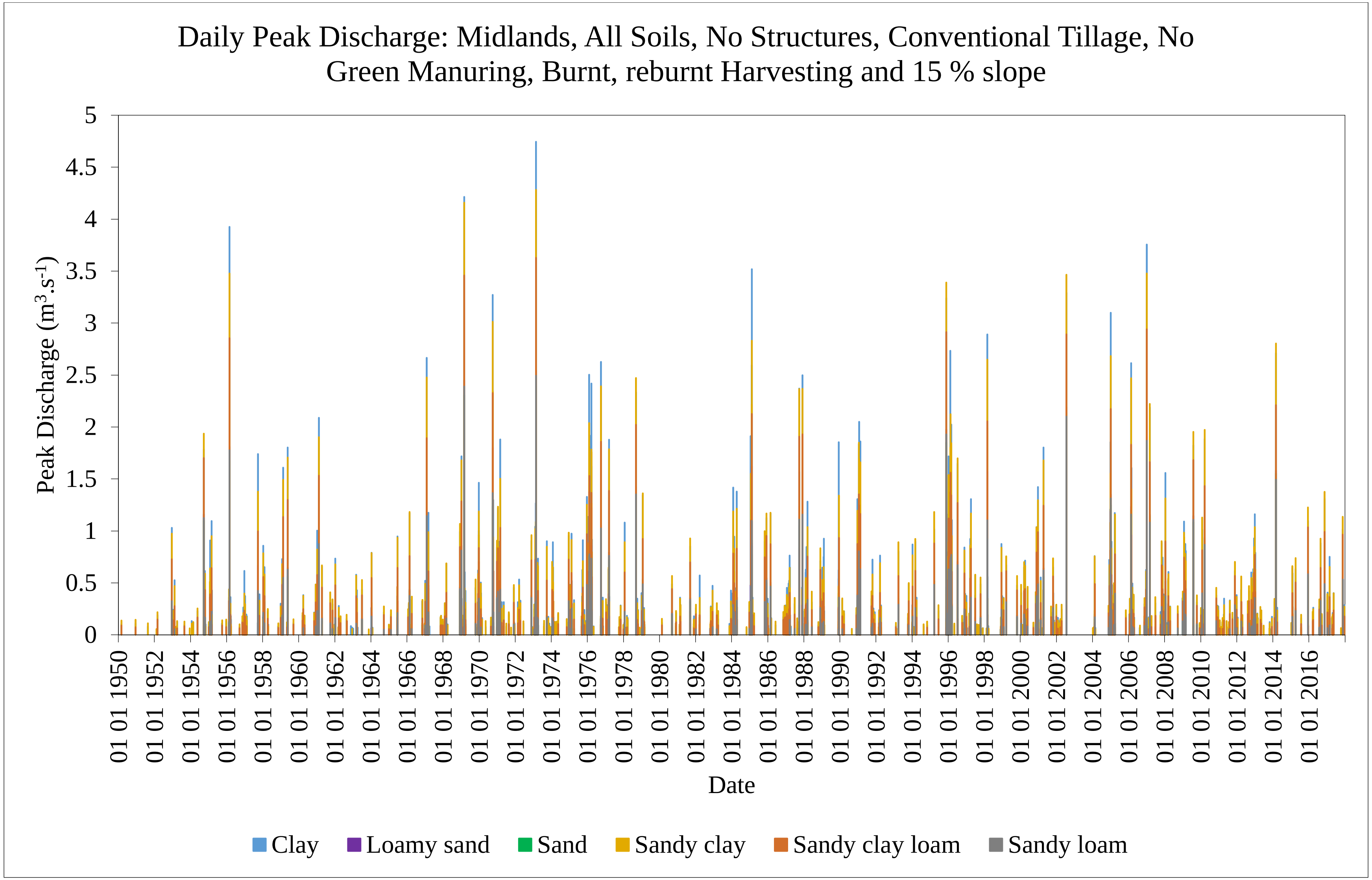

Figure 5.12 Daily peak discharge in the four regions

5.4.4 Comparison of designs from the CoSDT and the current sugar industry design nomograph for spacing of contour banks

The results of selected scenarios designed using the CoSDT and the current sugar industry design nomograph for spacing of contour banks are shown in Table 5.3 with discussions following thereafter. The design outputs from the CoSDT included horizontal and vertical intervals, and soil losses. On the other hand, design outputs from the current sugar industry design nomograph included horizontal and vertical intervals. The soil loss estimates from the current sugar industry design nomograph were calculated using the USLE and the various parameters extracted from Platford (1987).

Table 5.3 Select scenarios designed with the CoSDT and the current sugar industry design nomograph for spacing of contour banks

Variable	CoSDT				Current Sugar Industry Design Nomograph
Region	South Coast	North Coast	Zululand and Irrigated	Midlands	All
Horizontal interval (m)	32[a] [-62]	48[a] [-44]	37[a] [-56]	140[a] [65]	85[a]
	13[b] [-83]	29[b] [-63]	24[b] [-69]	140[b] [79]	78[b]
	9[c] [-82]	18[c] [-64]	13[c] [-74]	140[c] [180]	50[c]
Vertical interval (m)	6[a] [-63]	9[a] [-44]	7[a] [-56]	27[a] [69]	16[a]
	2[b] [-86]	6[b] [-57]	5[b] [-64]	27[b] [93]	14[b]
	2[c] [-80]	4[c][-60]	3[c][-70]	27[c] [170]	10[c]
Soil loss ($t.ha^{-1}.year^{-1}$)	5.00[a] [1]	5.00[a] [1]	4.77[a] [-4]	0.36[a] [-93]	4.96[a]
	5.00[b] [-34]	5.00[b] [-34]	5.00[b] [-34]	0.50[b] [-93]	7.56[b]
	5.00[c] [-85]	5.00[c] [-85]	5.00[c] [-85]	1.57[c] [-95]	32.59[c]

[a] Contour bank spacing for the sandy clay loam (moderate erodibility for current sugar industry design nomograph), 20% slope, water carrying terrace, minimum tillage, no green manuring, and mulched with strip/ panel harvesting scenario.

[b] Contour bank spacing for the sandy clay loam (moderate erodibility for current sugar industry design nomograph), 20% slope, water carrying terrace, minimum tillage, no green manuring, and burnt and reburnt harvesting scenario.

[c] Contour bank spacing for the sandy clay loam (moderate erodibility for current sugar industry design nomograph), 20% slope, water carrying terrace, conventional tillage, no green manuring, and burnt and reburnt harvesting scenario

[ ] Percentage deviation from Current Sugar Industry Design Nomograph (*i.e.* Percentages based on deviation from designs conducted with the current sugar industry design nomograph)

Differences exist between spacings of contour banks designed using the CoSDT and the current sugar industry design nomograph as shown in Table 5.3. The differences result in both larger and smaller contour spacing depending on the scenario. The horizontal spacing of water carrying terraces designed using the current sugar industry design nomograph is greater than the horizontal spacing designed with the CoSDT for the South Coast, North Coast and Zululand and Irrigated regions while it is less than the horizontal spacing for the Midlands as shown by the percentage deviations in the square brackets.

The differences in the spacings of contour banks designed using the CoSDT and the current sugar industry design nomograph are attributed to the fact that Platford (1987) developed the sugar industry design nomograph using the USLE and average parameter values representing the entire sugar industry while the CoSDT was developed using the MUSLE and parameters representative of each region in the sugar industry. To highlight the differences in the ULSE and MUSLE parameters, the USLE parameters corresponding to the designs from the sugar industry design nomograph were extracted from Platford (1987) and compared against the respective MUSLE parameters used in the simulations leading to the development of the CoSDT**Error! Reference source not found.**.

One of the major sources of differences is in the *R* factor and the storm flow factor which drive erosion in the USLE and sediment yield in the MUSLE respectively, as shown in Figure 5.13. In the development of the sugar industry design nomograph, Platford (1987) used an average *R* factor of 300 $MJ.mm.ha^{-1}.h^{-1}$ for the entire sugar industry and yet rainfall erosivity is not uniformly distributed throughout the year as reported by Renard *et al.* (1991). On the other hand, the MUSLE storm flow factors used in the development of the CoSDT vary across regions with their impacts on sediment yield and subsequent spacings of contour banks dependent on the crop cover.

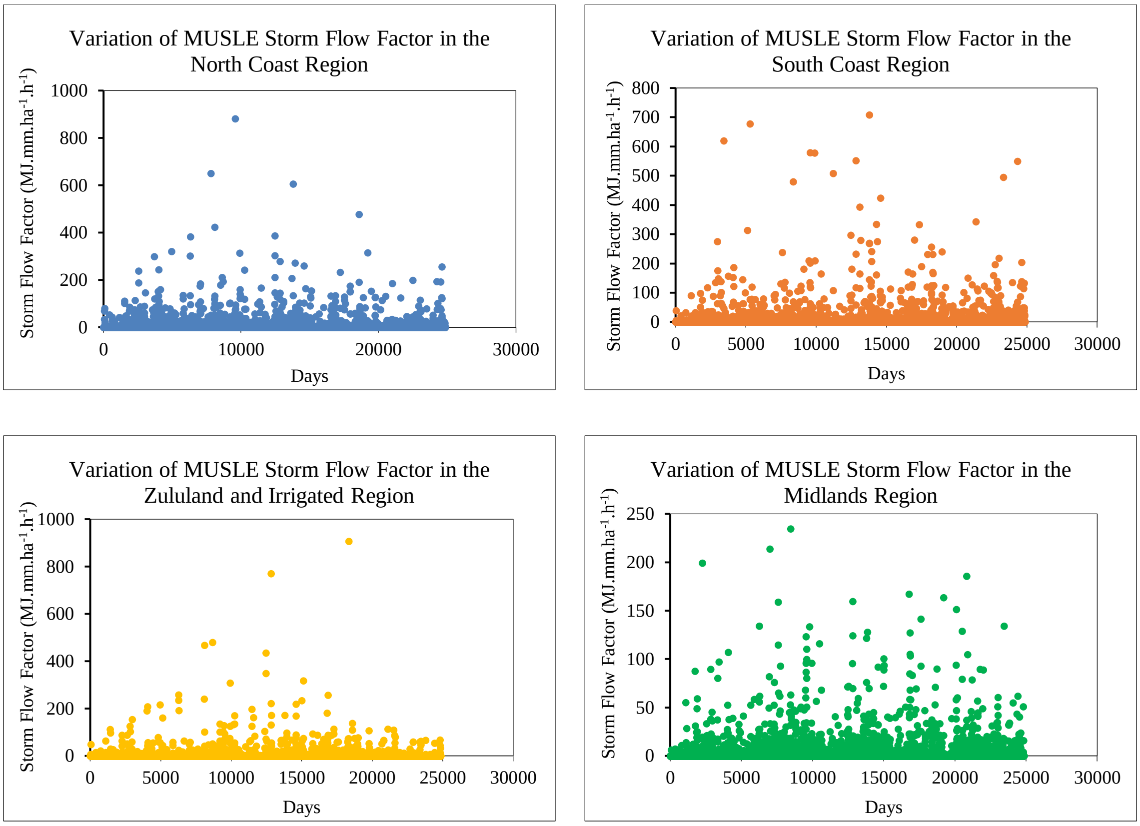

Figure 5.13 Variation of MUSLE storm flow factors in the four regions

Furthermore, the differences in the spacings of contour banks designed using the CoSDT and the current sugar industry design nomograph are attributed to the variations in the erosion causing factors (*i.e.* *K*, *C* and *P*) used in the development of the sugar industry design nomograph and the CoSDT. To highlight the differences, erosion causing factors from three scenarios (*i.e.* a, b, and c) are summarised in Table 5.4**Error! Reference source not found.**.

Table 5.4 Parameters from the CoSDT and the current sugar industry design nomograph

Scenario	a		b		c	
Parameter	CoSDT	Current Sugar Industry Design Nomograph	CoSDT	Current Sugar Industry Design Nomograph	CoSDT	Current Sugar Industry Design Nomograph
K	0.38	0.28	0.38	0.28	0.38	0.28
C	0.01 – 0.60	0.11	0.01 – 0.60	0.11	0.01 – 0.60	0.11
P	0.15	0.08	0.15	0.14	0.15	0.77

[a] Contour bank spacing for the sandy clay loam (moderate erodibility), 20% slope, water carrying terrace, minimum tillage, no green manuring and mulched with strip/ panel harvesting scenario.

[b] Contour bank spacing for the sandy clay loam (moderate erodibility), 20% slope, water carrying terrace, minimum tillage, no green manuring and burnt and reburnt harvesting scenario.

[c] Contour bank spacing for the sandy clay loam (moderate erodibility), 20% slope, water carrying terrace, conventional tillage, no green manuring and burnt and reburnt harvesting scenario

For example, Platford (1987) used a constant *C* factor of 0.11 for the entire sugar industry while varying *C* factors (*i.e.* 0.01 – 0.60) were used in the development of the CoSDT as shown in Figure 5.14. Stationary sugarcane cover factors are not realistic as the *C* factors vary depending on the stage of growth (Tanyaş *et al.*, 2015). In addition, the *P* factor used by Platford (1987) is an aggregation of harvesting, terracing and tillage practices while in the CoSDT, the *P* factor represents terracing only with harvesting practices varied within the *C* factor since harvesting impacts on sugarcane cover.

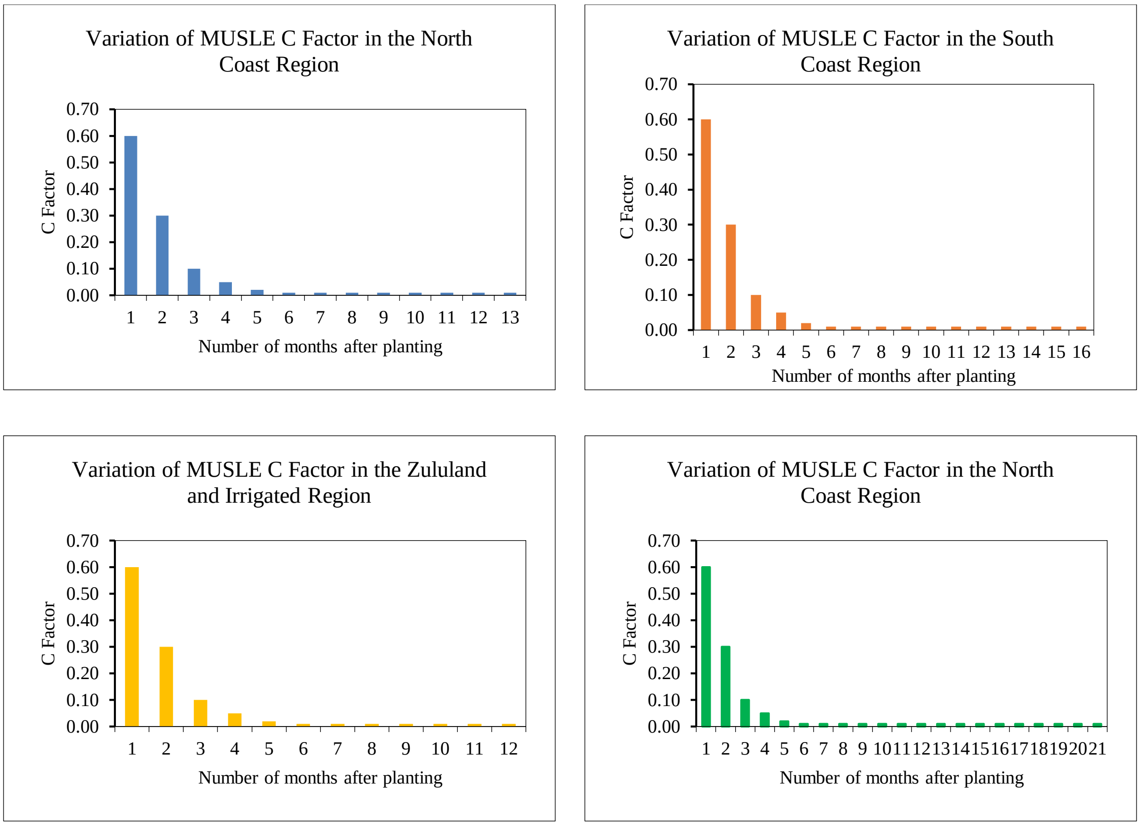

Figure 5.14 Variation of MUSLE *C* factors in the four regions

It is also important to note that Platford (1987) used subjective judgement in the development of the current sugar industry design nomograph and this could be another source of discrepancies.

5.4.5 Comparison of designs from LUPs prepared by specialists in the sugar industry and designs from the CoSDT

The results of available designs from LUPs prepared by Naude and Makhaye (2018) and Wilkinson and Gumede (2018), who are specialists in the sugar industry, and the same designs conducted with the CoSDT are presented on a regional basis in Sections 5.4.5.1 to 5.4.5.4. The soil loss estimates from designs prepared by specialists in the sugar industry were calculated using the USLE and the various parameters estimated by Platford (1987). On the other hand, the MUSLE soil losses were obtained by accumulating simulated individual sediment yield events on an annual basis and averaged for the entire period (*i.e.* 68 years).

5.4.5.1 North Coast

A summary of designs in the North Coast are presented in Table 5.5 and the discussion follows shortly.

Table 5.5 Designs from LUPs and the CoSDT for spacing of contour banks in the North Coast

Farm	Climax Sugar (Field 18)		Emboni		Hopewell		Savannah Dancer	
Variable / Design Tool	Specialists' designs	CoSDT	Specialists' designs	CoSDT	Specialists' designs	CoSDT	Specialists' designs	CoSDT
Soil texture/ Erodibility	Erodible	Loamy sand	Erodible	Sandy loam	Erodible	Loamy sand	Erodible	Loamy sand
Slope (%)	10	10	16	16	23	23	15	15
Structure	Water carrying terrace							
Tillage type	Conventional tillage	Conventional tillage	Minimum tillage	Minimum tillage	Minimum tillage	Minimum tillage	Minimum tillage	Minimum tillage
Agronomic practice	No green manuring							
Harvesting method	Burnt and scattered tops	Burnt and scattered tops	Mulched	Mulched	Mulched	Mulched	Mulched	Mulched
Horizontal interval (m)	60	60 [0]	38	60 [58]	39	21 [-46]	40	60 [50]

Farm	Climax Sugar (Field 18)		Emboni		Hopewell		Savannah Dancer	
Variable / Design Tool	Specialists' designs	CoSDT	Specialists' designs	CoSDT	Specialists' designs	CoSDT	Specialists' designs	CoSDT
Vertical interval (m)	6	6	6	10	8	5	6	9
Soil loss* ($t.ha^{-1}.year^{-1}$)	18.8	1.84 [-90]	4.4	3.66 [-17]	7.0	5.00 [-28]	4.2	3.30 [-21]

[ ] Percentage deviation of CoSDT designs from designs prepared by specialists in the sugar industry

* Soil losses from the specialists' designs were estimated using the USLE and parameters derived from Platford (1987)

The contour spacing from LUPs prepared by specialists in the sugar industry and the contour spacing of the same scenarios designed with the CoSDT are similar for Climax Sugar (Field 18) farm. However, the spacing from the CoSDT is wider than the spacing from specialists' designs for Emboni and Savannah Dancer farms, and narrower for Hopewell farm with differences of 50% as shown by the percentage deviations in the square brackets in Table 5.5. In addition, soil loss estimates from the CoSDT are less than soil loss estimates from the specialists' designs with deviations of over 20% for minimum tillage practices and 90% for conventional tillage practices. The *R* factor which is the driver of erosion in the USLE was fixed to 300 $MJ.mm.ha^{-1}.h^{-1}$ as shown in **Error! Reference source not found.** and yet rainfall e rosivity is not uniformly distributed throughout the year as reported by Renard *et al.* (1991). Similarly, the *C* factor used in the USLE to estimate erosion was fixed and yet *C* factors vary depending on the stage of crop growth as demonstrated by Alexandridis *et al.* (2015). With regards to the MUSLE, the stormflow factor for the North Coast varies between 1 and 841 $MJ.mm.ha^{-1}.h^{-1}$, while the *C* factors are in the 0.01 – 0.60 range (*i.e.* 0.60 at planting of sugarcane and 0.01 at full canopy establishment). The interactions between the *R* factor or stormflow factor, and the *C* factor impact on soil erosion and the subsequent spacing of contour banks. For example, in the MUSLE, high storm flow factors do not necessarily translate into high soil losses because of the variations in the *C* factor whereas in the USLE, the fixed *R* and *C* factors means that their impacts on soil loss is fixed. The fact that the USLE *R* and *C* factors are static implies that they are not realistic as documented by Renard *et al.* (1991) and Tanyaş *et al.* (2015) respectively. On the other hand, the MUSLE parameters used in the development of the CoSDT were based on acceptable *ACRU* verifications presented in Chapter 4 and therefore representative of conditions in the sugar industry of South Africa.

5.4.5.2 South Coast

A summary of designs in the South Coast are presented in Table 5.6 and the discussion follows shortly.

Table 5.6 Designs from LUPs and the CoSDT for spacing of contour banks in the South Coast

Farm	Larkhan		Morelands		Valleyview	
Variable / Design Tool	Specialists' designs	CoSDT	Specialists' designs	CoSDT	Specialists' designs	CoSDT
Soil texture/ Erodibility	Erodible	Sandy loam	Moderate	Sandy clay loam	Moderate	Sandy clay loam
Slope (%)	18	18	18	18	18	18
Structure	Water carrying terrace					
Tillage type	Minimum tillage					
Agronomic practice	No green manuring					
Harvesting method	Mulched					
Horizontal interval (m)	45	19 [-58]	35	17 [-51]	40	17 [-58]
Vertical interval (m)	8	3	6	3	7	3
Soil loss* ($t.ha^{-1}.year^{-1}$)	5.7	5 [-12]	3.3	5 [53]	3.5	5 [42]

[ ] Percentage deviation from designs prepared by specialists in the sugar industry

* Soil losses from the specialists' designs were estimated using the USLE and parameters derived from Platford (1987)

From Table 5.6, the designs from LUPs prepared by specialists in the sugar industry and the same scenarios designed with the CoSDT are different with the designed spacing from the CoSDT approximately half of those from the specialists' designs. The soil loss estimates from the CoSDT are greater than estimates from the specialists' designs for Morelands and Valleyview farms deviating by over 40% and less than estimates from Larkhan farm with a deviation of 12%. Similar to the North Coast region, it is possible that the parameters used in the development of the specialists' design tool are not representative of the South Coast region, hence the differences in designs. The USLE *R* and *C* factors are static as shown in**Error! Reference source not found.** Table 5.4 while the MUSLE storm flow and *C* factors are dynamic as shown in Figure 5.13 and Figure 5.14. Considering that rainfall erosivity is not uniformly distributed throughout the year as reported by Renard *et al.* (1991), and *C* factors vary with crop growth as reported by Tanyaş *et al.* (2015), the USLE *R* and *C* factors are not realistic and hence the source of differences between designs conducted with the CoSDT and by specialists in the sugar industry.

5.4.5.3 Zululand and Irrigated region

A summary of designs in the Zululand and Irrigated region are presented in Table 5.7 and the discussion follows shortly.

Table 5.7 Designs from LUPs and the CoSDT for spacing of contour banks in Zululand and Irrigated region

Farm	Bathenjini		Knoorhan Hill	
Variable / Design Tool	Specialists' designs	CoSDT	Specialists' designs	CoSDT
Soil texture/ Erodibility	Moderate	Clay	Erodible	Loamy sand
Slope (%)	8	8	20	20
Structure	Water carrying terrace			
Tillage type	Conventional tillage	Conventional tillage	Minimum tillage	Minimum tillage
Agronomic practice	No green manuring			
Harvesting method	Burnt and scattered tops	Burnt and scattered tops	Mulched with strip harvesting	Mulched with strip harvesting

Farm	Bathenjini		Knoorhan Hill	
Variable / Design Tool	Specialists' designs	CoSDT	Specialists' designs	CoSDT
Horizontal interval (m)	60	60 [0]	60	60 [0]
Vertical interval (m)	5	5	13.5	12
Soil loss* ($t.ha^{-1}.year^{-1}$)	9.2	0.90 [-90]	1.9	4.84 [151]

[ ] Percentage deviation from designs prepared by specialists in the sugar industry

* Soil losses from the specialists' designs were estimated using the USLE and parameters derived from Platford (1987)

The contour spacings from LUPs prepared by specialists in the sugar industry and the contour spacings of the same scenarios designed with the CoSDT are similar for Zululand and Irrigated region although large differences exist in the estimated soil losses as shown in Table 5.7. The discrepancies in soil loss estimates are attributed to the differences in model parameters of the MUSLE and USLE which were used in the CoSDT and specialists' designs respectively as shown in Table 5.8. For example at the Bathenjini farm, the *P* factor used in soil loss estimate from the specialists' design is an aggregation of harvesting, terracing and tillage practices while in the CoSDT, the *P* factor represents terracing only with harvesting practices varied within the *C* factor since harvesting impacts on sugarcane cover. In addition, the *C* factors used in the USLE are static whereas the *C* factors used in the MUSLE vary (*i.e.* 0.60 at planting of sugarcane and 0.01 at full canopy establishment).

Table 5.8 Parameters from the CoSDT and the specialists' design nomograph

Parameter	Bathenjini		Knoorhan Hill	
	CoSDT	Specialists' design	CoSDT	Specialists' design
K	0.19	0.28	0.60	0.42
C	0.01 – 0.60	0.11	0.01 – 0.60	0.11
P	0.14	0.69	0.04	0.03

5.4.5.4 Midlands region

A summary of designs in the Midlands region are presented in Table 5.9 and the discussion follows shortly.

The designs from LUPs prepared by specialists in the sugar industry and the same scenarios designed with the CoSDT are similar for Fat Acre farm while the designed spacing from the CoSDT varies by more than 33% of the design spacings from the current sugar industry design norms for Broadmoor/ Windy Hill, Klein Waterval, Stainbank Bros and Stony Hill farms, as shown in Table 5.9. Furthermore, large differences exist between the soil losses estimated from the two design tools with those estimated from the CoSDT very low compared to the specialists' design tool estimates. The *R* factor which is the driver of erosion in the USLE was fixed to 300 $MJ.mm.ha^{-1}.h^{-1}$ in the Midlands as shown in **Error! Reference source not found.** Table 5.4 and yet rainfall erosivity is not uniformly distributed throughout the year as reported by Renard *et al.* (1991). Similarly, the *C* factor used in the USLE to estimate erosion was fixed and yet *C* factors vary depending on the stage of crop growth as documented by Alexandridis *et al.* (2015) and shown in Figure 5.1. On the other hand, the MUSLE stormflow factor for the Midlands varies between 2 and 234 $MJ.mm.ha^{-1}.h^{-1}$ while the *C* factors are in the range 0.01 – 0.60 (*i.e.* 0.60 at planting of sugarcane and 0.01 at full canopy establishment). The interactions between the *R* factor or stormflow factor and the *C* factor impact on soil erosion and the subsequent spacing of contour banks and in the MUSLE, high storm flow factors do not necessarily translate into high soil losses as long as the soil surface is sufficiently protected by crop cover. The fact that the USLE *R* and *C* factors are static implies that they are not realistic as documented by Renard *et al.* (1991) and Tanyaş *et al.* (2015) respectively.. It is also important to note that the maximum MUSLE stormflow factor is approximately 75% of the USLE *R* factor. In addition, the sugarcane ratoon length in the Midlands is 21 months, hence offering great protection against erosion.

Table 5.9 Designs from LUPs and the CoSDT for spacing of contour banks in Midlands region

Farm	Broadmoor/ Windy Hill		Fat Acre		Klein Waterval		Stainbank Bros		Stony Hill	
Variable / Design Tool	Specialists' designs	CoSDT	Specialists' designs	CoSDT	Specialists' designs	CoSDT	Specialists' designs	CoSDT	Specialists' designs	CoSDT
Soil texture/ Erodibility	Resistant	Clay	Resistant	Clay	Moderate	Sandy clay loam	Erodible	Sand	Erodible	Sandy loam
Slope (%)	20	20	8	8	18	18	28	28	12	12
Structure	Water carrying terrace									
Tillage type	Conventional tillage									
Agronomic practice	No green manuring	No green manuring	No green manuring	No green manuring	No green manuring	No green manuring	Green manuring	Green manuring	Green manuring	Green manuring
Harvesting method	Burnt and scattered tops	Burnt and scattered tops	Burnt and scattered tops	Burnt and scattered tops	Burnt and scattered tops	Burnt and scattered tops	Burnt and scattered tops	Burnt and scattered tops	Burnt and scattered tops	Burnt and scattered tops
Horizontal interval (m)	35	60 [71]	60	60 [0]	35	60 [71]	30	60 [100]	45	60 [33]

Farm	Broadmoor/ Windy Hill		Fat Acre		Klein Waterval		Stainbank Bros		Stony Hill	
Variable / Design Tool	Specialists' designs	CoSDT	Specialists' designs	CoSDT	Specialists' designs	CoSDT	Specialists' designs	CoSDT	Specialists' designs	CoSDT
Vertical interval (m)	7	12	4	5	6	11	8	16	5	7
Soil loss* ($t.ha^{-1}.year^{-1}$)	25.3	0.72 [-97]	9.8	0.13 [-99]	28.3	0.60 [-98]	9.6	3.53 [-63]	4.3	0.07 [-98]

* Soil losses from the specialists' designs were estimated using the USLE and parameters derived from Platford (1987)

[ ] Percentage deviation from designs prepared by specialists in the sugar industry

5.5 Conclusions

In general, the largest amount of runoff was simulated in the North Coast followed by the South Coast, Midlands, and Zululand and Irrigated regions which is logical considering that rainfall was highest in the North Coast followed by the South Coast, Midlands, and Zululand and Irrigated regions. The respective MAPs are 1 146, 934, 818 and 642 mm. Furthermore, the largest amount of sediment yield was simulated for the South Coast followed by North Coast, Zululand and Irrigated and the Midlands regions and this is as a result of differences in rainfall intensities estimated from maps of rainfall distribution zones and ratoon lengths in the homogenous climatic zones. The respective 30 minute, 2 year rainfall intensities are 60, 53, 50 and 68 $mm.h^{-1}$ and ratoon lengths for the regions and 16, 13, 12 and 21 months, respectively.

In terms of soils, the North Coast, South Coast and Zululand and Irrigated regions exhibited similar relationships with loamy sands the most susceptible to erosion followed by sandy clay loams, sandy loams, sands, clays and sandy clays. The relationship exhibited is expected because sandier soils are less cohesive than clayey soils and hence more unstable and at greater risk of erosion. However, the Midlands showed a different relationship in soil erodibility. Clayey soils are more susceptible to erosion than the sandier soils with sandy clay loam being the most susceptible followed by clay, sandy clay, loamy sand, sandy loam and sand. It was initially suspected that the rainfall of higher intensity received in the Midlands region compared to the North Coast, South Coast and Zululand and Irrigated regions was responsible for the difference in relationships. This is because clayey soils have lower infiltration rates than sandier soils thus draining very slowly and increasing the risk of runoff which further increases the amount of sediment yield generated. However, further investigations on the effects of varying rainfall intensity to a distribution with lower intensity values showed that clayey soils were still more susceptible to erosion than sandier soils. Hence, it was postulated that relationship exhibited in the Midlands is attributed to the relatively low daily rainfall occurring more frequently compared to the North Coast, South Coast and Zululand and Irrigated regions. This is because, the frequently occurring low rainfall makes the soils wet and with clayey soils having poorer drainage than sandier soils, more runoff is generated from the clayey soils thus increasing the risk of sediment yield.

The CoSDT accounts for vulnerability during break cropping by including the green manuring agronomic practice while regional variations of climate and their impacts on soil erosion and runoff were addressed through using region specific climatic data in the simulations and subsequent development of the CoSDT. Furthermore, it is based on sustainable soil loss limits of 5 $t.ha^{-1}.year^{-1}$. The robustness of the CoSDT is ensured by the over 46 080 exhaustive scenarios contained in a database while its simplicity of use is in the fact that practices are selected from drop down menus of the MS Access graphical user interface. The scenarios are realistic in that they were conceptualised based on practices in the sugar industry identified from SASRI (2016) and consultations with stakeholders in the industry.

Comparison of designs of contour bank spacings from the CoSDT and the current sugar industry design nomograph showed both positive and negative differences, depending on the scenario and region. This was attributed to the fact that Platford (1987) developed the current sugar industry design nomograph using the USLE and average values representing the entire sugar industry while the CoSDT was developed using the MUSLE with parameters based on acceptable *ACRU* verifications presented in Chapter 4 and hence, representative of each region in the sugar industry. For example, the *R* factor which drives erosion in the USLE is static and constant and yet rainfall erosivity is not uniformly distributed throughout the year as documented by Renard *et al.* (1991). On the other hand, the storm flow factor which drives sediment yield in the MUSLE varies regionally and across regions. Similarly, static *C* factors are used in the USLE whereas *C* factors used in the MUSLE vary depending on stage of sugarcane growth (*i.e.* 0.60 at planting of sugarcane and 0.01 at full canopy establishment) as documented by Alexandridis *et al.* (2015). In addition, Platford (1987) reported that subjective judgement was used in the development of the current sugar industry design nomograph, and this could be another source of discrepancies. Similarly, differences in designs from LUPs prepared by specialists in the sugar industry and designs from the CoSDT generally exist and the reasons for the differences are similar to those presented under comparisons of designs of contour bank spacings from the CoSDT and the current sugar industry design nomograph.

In conclusion, the CoSDT is more representative of conditions in the sugar industry of South Africa, and it should be employed in place of the current sugar industry design nomograph developed by Platford (1987).

5.6 Acknowledgements

I am highly indebted to Ms I Thompson and Ms A Makhaye from SASRI and Mr D Wilkinson and Ms N Gumede from Noodsberg Cane Growers Association for provision of Land Use Plans for various areas in the sugar industry.

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5.8 Appendix 5.1: SASRI Design Nomograph

The SASRI design nomograph for the vertical interval and panel width is shown in Figure 5.15 in and Figure 5.16 respectively.

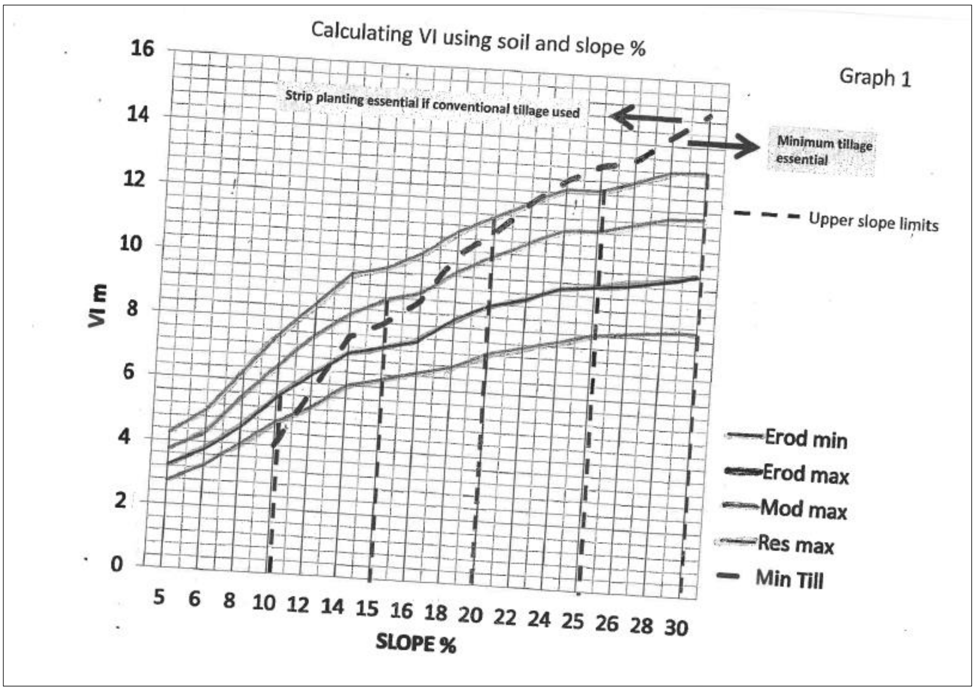

Figure 5.15 SASRI design nomograph for vertical intervals

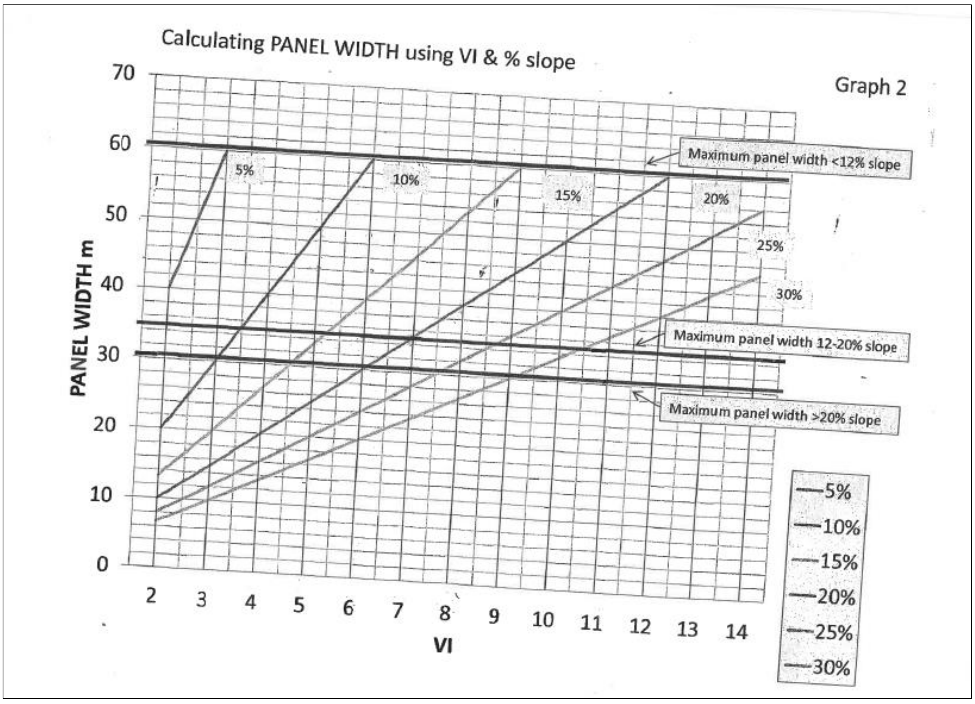

Figure 5.16 SASRI design nomograph for panel widths

5.9 Appendix 5.2: Slope-Effect Chart

The maximum permissible limits for the slope length and topographic factors for use in the MUSLE are shown in Figure 5.17.

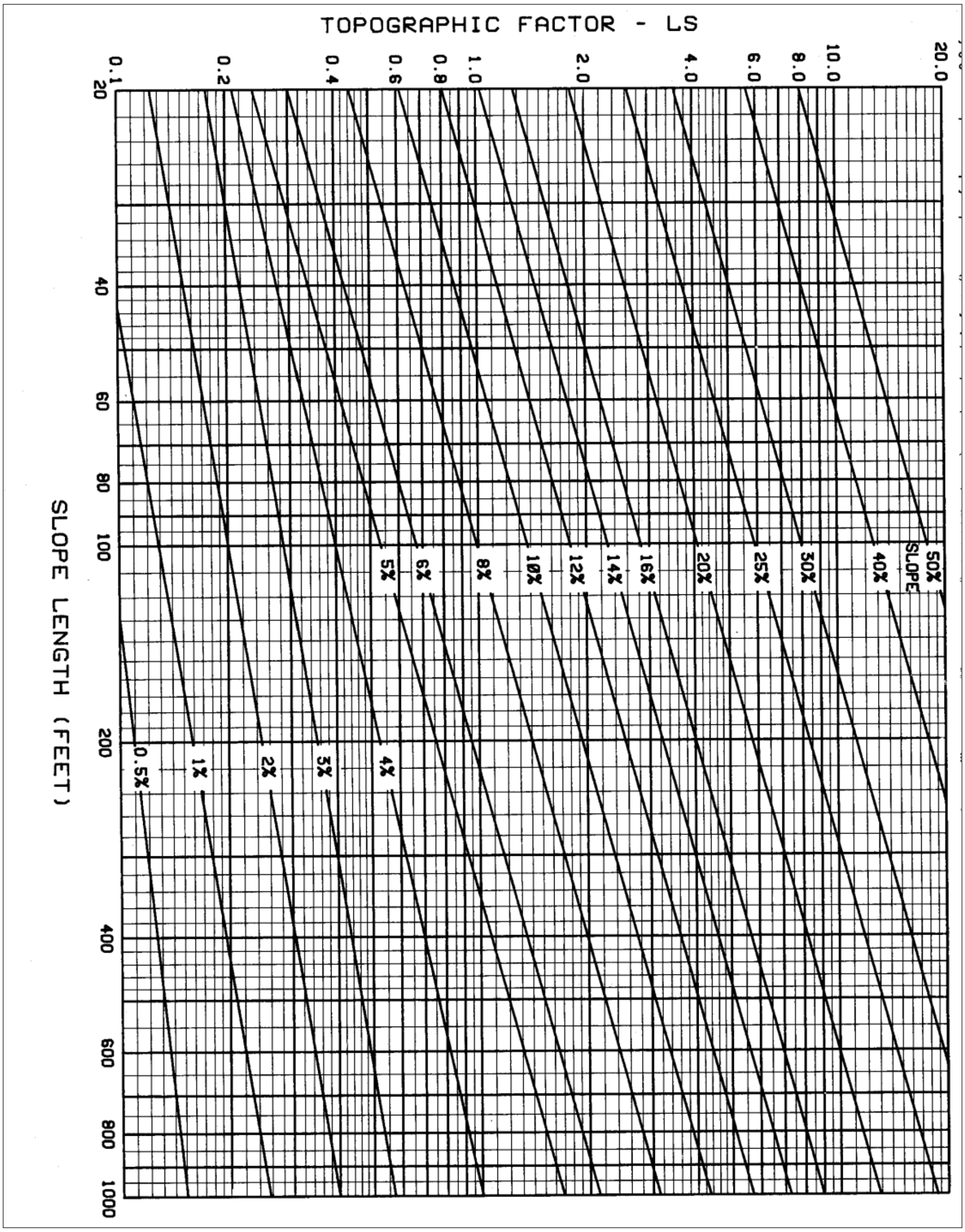

Figure 5.17 Slope-effect chart (Wischmeier and Smith, 1978)

5.10 Appendix 5.3: *ACRU* Parameters for the Simulation Scenarios used in the Development of the CoSDT for the Design of Soil and Water Conservation Structures in the Sugar Industry of South Africa

The various *ACRU* parameters employed in simulations used in the development of the updated tool for the design of soil and water conservation structures in the sugar industry of South Africa are shown in Table 5.10 to Table 5.20.

Table 5.10 Crop factors, *C* for sugarcane (after Smithers et al., 1996)

Months after planting	1	2	3	4	5	6	7	8	9	10	11	12
C factor (Summer)	0.60	0.30	0.10	0.05	0.02	0.01	0.01	0.01	0.01	0.01	0.01	0.01
C factor (Winter)	0.60	0.40	0.30	0.10	0.04	0.02	0.01	0.01	0.01	0.01	0.01	0.01

Table 5.11 Soil and streamflow variable and parameter selections for the *ACRU* model (Smithers *et al.*, 1995; Smithers *et al.*, 1996; Botha *et al.*, 1999; Lumsden *et al.*, 2003)

Variable/ Parameter*	Clay	Loamy sand	Sand	Sandy clay	Sandy clay loam	Sandy loam
DEPAHO	0.30	0.30	0.30	0.30	0.30	0.30
DEPBHO	0.50	0.50	0.50	0.50	0.50	0.50
WP1	0.222	0.079	0.065	0.179	0.131	0.089
WP2	0.234	0.097	0.087	0.206	0.149	0.097
FC1	0.337	0.176	0.159	0.289	0.234	0.187
FC2	0.363	0.207	0.193	0.332	0.267	0.208
PO1	0.482	0.432	0.430	0.423	0.402	0.448
PO2	0.482	0.432	0.430	0.423	0.402	0.448
ABRESP	0.15	0.70	0.80	0.40	0.50	0.65
BFRESP	0.15	0.70	0.80	0.40	0.50	0.65
SMAINI	0.50	0.50	0.50	0.50	0.50	0.50

Variable/ Parameter*	Clay	Loamy sand	Sand	Sandy clay	Sandy clay loam	Sandy loam
SMBINI	0.50	0.50	0.50	0.50	0.50	0.50
COIAM (BF)	0.35	0.35	0.35	0.35	0.35	0.35
COIAM (Sugarcane, minimum tillage and conservation structures)	0.40	0.40	0.40	0.40	0.40	0.40
COIAM (Sugarcane, minimum tillage and no structures)	0.32	0.32	0.32	0.32	0.32	0.32
COIAM (Sugarcane, conventional tillage and conservation structures)	0.25	0.25	0.25	0.25	0.25	0.25
COIAM (Sugarcane, conventional tillage and no structures)	0.20	0.20	0.20	0.20	0.20	0.20
SMDDEP (BF, Slope > 25%)	0.25	0.25	0.25	0.25	0.25	0.25
SMDDEP (BF, Slope < 25%)	0.30	0.30	0.30	0.30	0.30	0.30
SMDDEP (SP)	0.35	0.35	0.35	0.35	0.35	0.35
COFRU	0.009	0.009	0.009	0.009	0.009	0.009
QFRESP	0.90	0.90	0.90	0.90	0.90	0.90

*Key:

(BF)	Bare fallow value of the variable/parameter
(SP)	Value of the variable/parameter during sugarcane production
DEPAHO, DEPBHO	Thicknesses of top (A horizon) and subsoil (B horizon) respectively (m)
WP1, WP2	Permanent wilting points of top- and subsoil respectively ($m.m^{-1}$)
FC1, FC2	Drained upper limits of top- and subsoil respectively ($m.m^{-1}$)
PO1, PO2	Porosities of top- and subsoil horizons respectively ($m.m^{-1}$)
ABRESP	Saturated redistribution fraction from topsoil to subsoil
BFRESP	Saturated redistribution fraction from subsoil horizon to intermediate/groundwater store
COIAM	Coefficient of initial abstraction
SMDDEP	Effective depth of soil for stormflow response (m)
COFRU	Coefficient of base flow response

QFRESP Catchment stormflow response fraction

Table 5.12 Soil erodibility factors, *K* (Lorentz and Schulze, 1995; Smithers *et al.*, 1995)

Soil textural class	Soil erodibility	Soil erodibility class
Clay	0.19	Low
Sandy Clay	0.19	Low
Sandy Clay Loam	0.38	Moderate
Loamy Sand	0.60	High
Sand	0.60	High
Sandy Loam	0.60	High

Table 5.13 *ACRU* model variables for sugarcane under different geographical and management conditions (Schulze, 2013)

ACRU Variable	South Coast	North Coast	Zululand & Irrigated	KZN Midland
CAY	0.85	0.86	0.87	0.83
VEGINT	1.8	1.9	2.0	1.7
ROOTA	0.75	0.75	0.75	0.75

*Key:

CAY Crop coefficient

VEGINT Interception loss (mm.rainday^{-1})

ROOTA Fraction of effective root system in the topsoil horizon

Table 5.14 Support practices factors, *P* (Lorentz and Schulze, 1995; Renard *et al.*, 1997)

Slope (%)	Water Carrying Terrace		Spillover Road		No structure	
	No Strip	Strip	No Strip	Strip	No Strip	Strip
1	0.42	0.11	0.33	0.08	1.00	0.25
2	0.28	0.07	0.33	0.08	1.00	0.25
3	0.21	0.05	0.33	0.08	1.00	0.25
4	0.18	0.04	0.33	0.08	1.00	0.25

Slope (%)	Water Carrying Terrace		Spillover Road		No structure	
	No Strip	Strip	No Strip	Strip	No Strip	Strip
5	0.15	0.04	0.33	0.08	1.00	0.25
6	0.14	0.03	0.33	0.08	1.00	0.25
7	0.15	0.04	0.40	0.10	1.00	0.25
8	0.14	0.04	0.40	0.10	1.00	0.25
9	0.14	0.03	0.40	0.10	1.00	0.25
10	0.13	0.03	0.40	0.10	1.00	0.25
11	0.13	0.03	0.40	0.10	1.00	0.25
12	0.13	0.03	0.40	0.10	1.00	0.25
13	0.12	0.03	0.40	0.10	1.00	0.25
14	0.14	0.04	0.47	0.12	1.00	0.25
15	0.14	0.03	0.47	0.12	1.00	0.25
16	0.14	0.03	0.47	0.12	1.00	0.25
17	0.16	0.04	0.53	0.13	1.00	0.25
18	0.16	0.04	0.53	0.13	1.00	0.25
19	0.15	0.04	0.53	0.13	1.00	0.25
20	0.15	0.04	0.53	0.13	1.00	0.25
21	0.17	0.04	0.60	0.15	1.00	0.25
22	0.19	0.05	0.67	0.17	1.00	0.25
23	0.19	0.05	0.67	0.17	1.00	0.25
24	0.19	0.05	0.67	0.17	1.00	0.25
25	0.67	0.17	0.67	0.17	1.00	0.25
26	0.67	0.17	0.67	0.17	1.00	0.25
27	0.67	0.17	0.67	0.17	1.00	0.25
28	0.67	0.17	0.67	0.17	1.00	0.25
29	0.67	0.17	0.67	0.17	1.00	0.25
30	0.67	0.17	0.67	0.17	1.00	0.25
31	0.67	0.17	0.67	0.17	1.00	0.25
32	0.67	0.17	0.67	0.17	1.00	0.25
33	0.67	0.17	0.67	0.17	1.00	0.25
34	0.67	0.17	0.67	0.17	1.00	0.25

Slope (%)	Water Carrying Terrace		Spillover Road		No structure	
	No Strip	Strip	No Strip	Strip	No Strip	Strip
35	0.67	0.17	0.67	0.17	1.00	0.25
36	0.67	0.17	0.67	0.17	1.00	0.25
37	0.67	0.17	0.67	0.17	1.00	0.25
38	0.67	0.17	0.67	0.17	1.00	0.25
39	0.67	0.17	0.67	0.17	1.00	0.25
40	0.67	0.17	0.67	0.17	1.00	0.25

Table 5.15 Topographic factors, *LS* (Lorentz and Schulze, 1995; Renard *et al.*, 1997)

Slope (%)	Slope length, λ_1 (m)	Slope length factor, *L*	Slope steepness factor, *S*	Topographic factor, *LS*
1	305	1.48	0.14	0.20
2	305	1.90	0.25	0.47
3	305	2.26	0.35	0.80
4	305	2.58	0.46	1.19
5	305	2.86	0.57	1.63
6	305	3.11	0.68	2.11
7	305	3.34	0.78	2.62
8	305	3.54	0.89	3.16
9	305	3.73	1.01	3.75
10	305	3.89	1.17	4.56
11	305	4.05	1.34	5.41
12	305	4.19	1.50	6.29
13	305	4.32	1.67	7.19
14	305	4.44	1.83	8.12
15	305	4.55	1.99	9.06
16	305	4.65	2.15	10.03
17	305	4.75	2.32	11.00
18	305	4.84	2.48	11.99
19	305	4.93	2.64	13.00
20	305	5.01	2.79	14.00

Slope (%)	Slope length, λ_1 (m)	Slope length factor, *L*	Slope steepness factor, *S*	Topographic factor, *LS*
21	305	5.09	2.95	15.02
22	305	5.16	3.11	16.05
23	305	5.23	3.27	17.07
24	305	5.29	3.42	18.11
25	305	5.36	3.57	19.14
26	283	5.17	3.73	19.26
27	262	4.96	3.88	19.24
28	241	4.74	4.03	19.09
29	219	4.50	4.18	18.79
30	198	4.23	4.33	18.33
31	186	4.09	4.47	18.32
32	174	3.94	4.62	18.22
33	162	3.78	4.76	18.03
34	151	3.62	4.91	17.74
35	139	3.44	5.05	17.36
36	127	3.25	5.19	16.87
37	115	3.05	5.33	16.28
38	103	2.85	5.47	15.56
39	91	2.63	5.60	14.72
40	79	2.39	5.74	13.74

Table 5.16 Crop factor, *C* for green manure crops (Lorentz and Schulze, 1995; Schulze, 1995b; Smithers and Schulze, 1995; Renard *et al.*, 1997)

Months after planting	1	2	3	4	5	6
C factor for soy bean	0.40	0.10	0.04			
C factor for oats	0.21	0.11	0.07	0.14	0.08	0.10

Table 5.17 *ACRU* model variables for cover crops (Smithers *et al.*, 1995; Schulze, 2018)

ACRU Variable	Soy bean	Oats
CAY	0.35	0.28
VEGINT	0.68	0.63
ROOTA	0.92	0.82

Table 5.18 Crop factor, *C* for sugarcane depending on method of harvesting

Harvesting method	*C* factor
Burnt and reburnt (no surface residue)	0.60
Burnt and tops scattered	0.54
(d) Mulched	0.48

Table 5.19 Rainfall distribution type, 1 day, 2 year maximum rainfall, intensity multiplication factor and the 30 minute,2 year rainfall intensity for the different homogenous regions

Region	Rainfall distribution type	1 day, 2 year maximum rainfall (mm)	Intensity multiplication factor	30 minute, 2 year rainfall intensity, i_{30} ($mm.h^{-1}$)
South Coast	2	90	0.664	60
North Coast	2	80	0.664	53
Midlands	3	70	0.974	68
Zululand and Irrigated	2	75	0.664	50

Table 5.20 Catchment lag times for the different homogenous regions

Slope (%)	Lag Time (h)			
	North Coast	South Coast	Midlands	Zululand and Irrigated
1	6.99	5.04	3.88	3.90
2	5.68	4.09	3.15	3.17

Slope (%)	Lag Time (h)			
	North Coast	South Coast	Midlands	Zululand and Irrigated
3	5.03	3.62	2.79	2.81
4	4.61	3.32	2.56	2.58
5	4.31	3.11	2.39	2.41
6	4.08	2.94	2.27	2.28
7	3.90	2.81	2.16	2.18
8	3.75	2.70	2.08	2.09
9	3.62	2.60	2.01	2.02
10	3.50	2.52	1.94	1.96
11	3.40	2.45	1.89	1.90
12	3.32	2.39	1.84	1.85
13	3.24	2.33	1.80	1.81
14	3.17	2.28	1.76	1.77
15	3.10	2.23	1.72	1.73
16	3.04	2.19	1.69	1.70
17	2.99	2.15	1.66	1.67
18	2.94	2.12	1.63	1.64
19	2.89	2.08	1.60	1.61
20	2.85	2.05	1.58	1.59
21	2.80	2.02	1.56	1.57
22	2.77	1.99	1.53	1.54
23	2.73	1.97	1.51	1.52
24	2.69	1.94	1.50	1.51
25	2.66	1.92	1.48	1.49
26	2.63	1.89	1.46	1.47
27	2.60	1.87	1.44	1.45
28	2.57	1.85	1.43	1.44
29	2.55	1.83	1.41	1.42
30	2.52	1.82	1.40	1.41
31	2.49	1.80	1.38	1.39
32	2.47	1.78	1.37	1.38
33	2.45	1.76	1.36	1.37
34	2.43	1.75	1.35	1.36
35	2.41	1.73	1.34	1.34
36	2.39	1.72	1.32	1.33
37	2.37	1.70	1.31	1.32
38	2.35	1.69	1.30	1.31
39	2.33	1.68	1.29	1.30

Slope (%)	Lag Time (h)			
	North Coast	South Coast	Midlands	Zululand and Irrigated
40	2.31	1.66	1.28	1.29

6 INVESTIGATION OF SYSTEM DESIGN CRITERIA AND THE ECONOMIC IMPACT OF VARYING DESIGN RETURN PERIODS FOR SOIL AND WATER CONSERVATION STRUCTURES

This Chapter is under review in *Applied Engineering in Agriculture Journal*

Otim, D, Smithers, JC, Senzanje, A and van Antwerpen, R. “In press”. Investigation of system design criteria for extreme events leading to most soil loss and the economic impact of varying design return periods. *Applied Engineering in Agriculture* “In press”.

Abstract

The commonly employed structures in soil and water conservation are waterways and contour banks but it is recommended that soil management practices and agronomic measures are employed in conjunction with soil and water conservation structures for control of runoff and minimising soil erosion from cultivated lands. Design of conservation structures includes both hydrologic and hydraulic designs. Hydrologic design involves estimation of design floods which are required for the sizing of the hydraulic structures. The minimum recommended return period for the design of conservation structures is 10 years (Matthee and Van Schalkwyk, 1984; SASA, 2002; ASABE, 2012; Carey *et al.*, 2015) but due to the projected levels of risk, and the fact that a few large events are likely to be responsible for the majority of the erosion, the 10 year return period currently recommended may be inadequate (Otim *et al.*, 2019). Risk assessment involves trade-offs between risk avoidance and cost, hence, selection of a design return period should be appropriate to the level of risk of failure. The objective of this study was to investigate system design criteria and the economic impact of varying design return periods for soil and water conservation structures in the sugar industry of South Africa. The study area encompasses sugarcane growing areas in South Africa (*i.e.* South Coast, North Coast, Zululand and Irrigated and Midlands) as described in Chapter 5. Observed rainfall data, and runoff, peak discharge and sediment yield simulated using the Agricultural Catchments Research Unit (*ACRU*) model for the four homogenous climatic zones was utilised together with assumptions which are also presented in Chapter 5. The simulated scenarios were conceptualised based on practices in the sugar industry and consultations with stakeholders in the industry. In order to establish the annual events which contribute the major portions of annual sediment yield, non-zero sediment yield events were extracted from the simulated results, and the relationships between extreme events of sediment yield and the rainfall, runoff and peak discharge events associated with them, and the economic impact of varying design return periods was investigated. Furthermore, sediment yield events corresponding to four return periods (*i.e.* 10, 20, 25 and 50 years) were extracted from the simulations and their return periods compared against return periods of same day events for rainfall, runoff and peak discharge. Parabolic shapes of hydraulic sections with varying return periods were sized, cost estimates established and compared against costs of the 10 year return period designs. The results show that very few sediment yield events (*i.e.* 0.2%) contributed 21% to 95% of the annual sediment yield. Hence, the design of soil and water conservation structures should be based on the few sediment yield events contributing most of the erosion. In addition, extreme sediment yield events were not necessarily caused by extreme rainfall, runoff and peak discharge events, as the variations in crop cover at different stages of sugarcane growth play a major role in the sediment yield generated. Based on the sustainable soil loss of 5 $t.ha^{-1}$, the 20 year return period was recommended for the design of soil and water conservation structures, and the cost implication of varying design return periods from 10 to 20 year return period ranged between 16% and 35% across the four regions. Therefore, based on the fact that soil erosion is associated with adverse effects on sustainable crop production and also increases in costs of replanting destroyed crops, the 20 year return period should be adopted in the design of soil and water conservation structures.

Keywords*:* design criteria, erosion, economic impact, return period, risk, soil and water conservation

6.1 Introduction

Waterways and contour banks are widely used structures in soil and water conservation and their designs entail both hydrologic and hydraulic designs (Otim *et al.*, 2019). However, it is recommended that soil management practices and agronomic measures are employed together with soil and water conservation structures for proper control of runoff and soil erosion from cultivated lands (Morgan, 2005; Sustainet, 2010; Krois and Schulte, 2014; Reinders *et al.*, 2016). The aim of soil and water conservation is to ensure that the rate of soil formation is not exceeded by the rate of soil loss (Morgan, 2005) and, in the sugar industry of South Africa, sustainable soil losses are in the range 5 – 10 $t.ha^{-1}.year^{-1}$ (Matthee and Van Schalkwyk, 1984;

Le Roux *et al.*, 2008). Moreover, maintaining soil losses within sustainable limits is paramount in sustaining crop yields from cultivated lands because crop yield reduces with increases in soil loss (Russell, 1998). However, most of the erosion occurs during relatively few events and consideration should be given to individual rainfall events which initiate key hydrological responses such as stormflow and sediment yield (Schulze *et al.*, 2011). Hydrologic design encompasses design flood estimation which is required for the sizing of hydraulic structures, thereby quantifying and limiting the risk of failure of the structures (Reinders *et al.*, 2016). According toASABE (2012), the 1-day, 10 year storm is the minimum recommended rainfall event used in the design of soil and water conservation structures. In Australia, a 10 year return period is also recommended for the design of soil conservation structures but where failure would lead to severe damage, larger return periods are recommended (Carey *et al.*, 2015). For South Africa, it is recommended that soil conservation structures should be designed to accommodate 10 – 25 year return period floods (Matthee and Van Schalkwyk, 1984), while SASA (2002) specifies a 10 year return period for the design of soil and water conservation structures in the sugar industry. However, the 10 year return period currently recommended may not be adequate due to the projected levels of risk and the fact that a few large events are likely to be responsible for the majority of the erosion (Otim *et al.*, 2019). Therefore, the objective of this paper was to investigate system design criteria and the economic impact of varying design return periods for soil and water conservation structures in the sugar industry of South Africa.

6.1.1 Risk and return period

Design flood estimation is required for the design of hydraulic structures and the quantification and limitation of their risk of failure (Reinders *et al.*, 2016). Risk involves trade-offs between risk avoidance and cost (Rootzén and Katz, 2013). Therefore, the selection of a design return period should be appropriate to the level of risk of failure. The risk of failure is quantified as the probability of exceedance and is computed using Equation 6.1 (Reinders *et al.*, 2016).

$$P_e = \frac{1}{T} \tag{6.1}$$

where

P_e = probability of exceedance, and

T = return period (year).

6.1.2 Hydraulic design of soil and water conservation structures

Manning's equation for open channel flow is used in the hydraulic design of contour banks and waterways (Reinders *et al.*, 2016). Contour banks are constructed across a slope in order to intercept runoff water (Matthee and Van Schalkwyk, 1984) and safely discharge it into stable grassed waterways or natural drains (Carey *et al.*, 2015). The velocity of flow in open channels, v (m.s^{-1}) is determined from the hydraulic radius, R (m), Manning's roughness coefficient, n, and the slope of channel, S (m.m^{-1}), as illustrated in Equation 6.2.

$$v = \frac{1}{n} \times R^{2/3} \times S^{0.5} \qquad (6.2)$$

Generally, slopes and permissible velocities of grass lined water carrying terraces vary between 0.25% and 1.5%, and 0.45 m.s^{-1} and 1.8 m.s^{-1} respectively, whereas the respective slopes and permissible velocities of grassed waterways vary between 1% and 14%, and 0.6 m.s^{-1} and 1.8 m.s^{-1} (Matthee and Van Schalkwyk, 1984). According to Reinders *et al.* (2016), grassed channels are designed for both stability and capacity conditions. Stability design corresponds to conditions when vegetation has recently been established or cut short while capacity design corresponds to conditions when the vegetation is fully established in the water channel.

6.1.3 Costs of soil and water conservation structures

The effects of erosion on sustainable crop production and on increased costs of seeds for replanting destroyed crops are a major concern to most farmers (Shaxson, 1985). According to Morgan (2005), the installation and maintenance of many soil and water conservation structures is costly though farmers are willing to adopt conservation practices as long as substantial benefits accrue and the investment costs can be recovered. It is difficult to assess returns on investments in soil and water conservation, and studies on the economic returns of investment in soil and water conservation are few in Africa (Reij *et al.*, 2013).

The costs of construction of soil and water conservation structures include both labour costs and material costs (Barbier, 1990) and machinery costs (SASRI, 2019a; SASRI, 2019b). The cost of contour bank construction is significantly impacted by the location of the soil borrowed for its construction (USDA-NRCS, 2011). Labour requirements for soil conservation structures are frequently found to be excessive (Young, 1989). According to Morgan (2005), there is no adequate information on pricing labour as much of it is in form of unpaid inputs from farmers and their families.

Machines used in the construction of soil and water conservation structures include scrapers, bull dozers, road graders and farm ploughs (mould board or disc) (Matthee and Van Schalkwyk, 1984). According to McAlister and Russel (1998), a three-furrow disc plough, two- furrow reversible plough and grader require 12, 35 and 10 rounds respectively for the construction of a water carrying terrace with a drainage cross-sectional area of 0.5 m^2. Generally for mechanisation purposes, long narrow fields are preferred over short wide fields because of the savings in operational efficiency realised (Tweddle, 2019). Typical machinery and equipment costs for the construction of soil and water conservation structures in the sugar industry of South Africa are listed in Table 6.1.

Table 6.1 Machinery and equipment costs for construction of soil and water conservation structures (after SASRI, 2019b)

Machinery and equipment	Working width (m)	Efficiency (%)	Operation cost on lighter soils (R.ha^{-1})	Operation cost on heavier soils (R.ha^{-1})
60 kW tractor, 2-furrow reversible mould board plough	0.8	85	1112	1220
60 kW tractor, 2-furrow mould board plough	0.8	80	898	1004
60 kW tractor, 3-furrow reversible mould board plough	1.2	85	914	986
60 kW tractor, chisel plough	2.0	90	488	522

6.2 Methods and Assumptions

This section reports on the use of rainfall data and results of simulations of runoff, peak discharge and sediment yield using the Agricultural Catchments Research Unit (*ACRU*) model (Schulze, 1975) for the four homogenous climatic zones (*i.e.* South Coast, North Coast, Zululand and Irrigated and Midlands) in the sugar industry of South Africa, based on the study area, methodology and assumptions presented in Chapter 5. In general, the scenarios simulated were conceptualised based on practices in the sugar industry and consultations with stakeholders in the industry. It is important to note that over 46 080 scenarios were simulated as reported in Chapter 5 but, for purposes of this study, only a few selected scenarios were used.

6.2.1 Distribution of sediment yield events

Simulations representing a typical and poor soil conservation practice (*i.e.* no structures, conventional tillage, no green manuring, burnt, re-burnt harvesting practice and 40% slope) from each of the regions were used in the analysis of distribution of sediment yield events.

Non-zero sediment yield events were extracted, counted and summed on an annual basis, and plots of the number of annual sediment yield events and annual sediment yield against calendar years made. The purpose was to establish annual events which make up the major portion of annual sediment yield.

6.2.2 Investigation of relationships between large sediment yield events and the associated rainfall, runoff and peak discharge events

In order to conduct this investigation, simulations from the worst case scenario leading to the most extreme events of sediment yield (*i.e.* no structures, conventional tillage, no green manuring, burnt, re-burnt harvesting practice and 40% slope) in each of the regions were employed. Considering that only a few events lead to the generation of the annual sediment yield, analyses were restricted to the non-zero sediment yield events and return periods calculated using Equation 6.1. Sediment yield events equivalent to four return periods (*i.e.* 10, 20, 25 and 50 years) were extracted from the simulations and their return periods compared against the return periods of same day events for rainfall, runoff and peak discharge. Selection of the four return periods was undertaken bearing in mind the total length of record used in analysis (*i.e.* 68 years) and the aim was not to exceed the 68 years.

In addition, return periods corresponding to the sustainable soil loss of 5 $t.ha^{-1}$ were calculated and compared with same day return periods for rainfall, runoff and peak discharge which were also calculated from Equation 6.1. The sole purpose was to recommend a suitable return period for the design of soil and water conservation structures from a sediment yield perspective. Hence, the largest of the rainfall, runoff and peak discharge return periods over the period of record, was recommended for the design of soil and water conservation structures provided it was greater than the minimum recommended 10 year return period. In the event, that the largest of the rainfall, runoff and peak discharge return periods was less than the minimum recommended 10 year return, the 10 year return was recommended.

6.2.3 Investigation of the economic impact of varying design return periods

Parabolic sections of hydraulic structures were assumed because they allow planting of sugarcane in them and movement of vehicles over the structures. It was also assumed that waterways remained similar for all design return periods, hence, sizing of structures was only conducted for water carrying terraces. Parabolic cross-sectional areas of water carrying terraces were sized for the minimum 10 year return period and the newly recommended return period discharges estimated using Equation 6.2 and the costs of implementing the different designs estimated. It was assumed that the parabolic sections were grassed lined with permissible velocities of 0.9 $m.s^{-1}$ and slopes of 0.5%. It was further assumed that a 60 kW tractor and two-furrow reversible mould board plough were used in the construction of water carrying terraces and rates in Table 6.1 used to cost the operation of constructing one water carrying terrace on 1 ha narrow long strip of land. It is important to note that the costs are for construction only and do not cover ongoing maintenance.

According to McAlister and Russel (1998), a two-furrow reversible mould board plough would require 35 rounds to construct a water carrying terrace with a drainage cross-sectional area of 0.5 m^2. Therefore, costing of the various designed sections was undertaken by prorating the cost of construction of a 0.5 m^2 cross-sectional area (*i.e.* 1 112 $R.ha^{-1}$). Cost comparisons between the 10 year return period designs and designs based on the recommended higher return period were undertaken so as to establish the economic impact of varying design return periods from the minimum recommended 10 year return period to the newly recommended return period.

6.3 Results and Discussion

The results and discussions of the distribution of event sediment yield, investigation of relationships between extreme events of sediment yield and the rainfall, runoff and peak discharge events associated with them, and the economic impact of varying design return periods, are presented below. Similar to Chapter 5, only a few scenarios have been selected for discussion. However, the trends exhibited are similar irrespective of the scenario.

6.3.1 Event sediment yield distributions

Plots of the number of annual sediment yield events and summation of sediment yield on an annual basis are shown in Figure 6.1 and Figure 6.3 respectively. It is evident in Figure 6.1 that the number of events contributing to annual sediment yield vary annually and across regions. The variation in total number of sediment yield events contributing to annual sediment yield in a given region is attributed to the variations in temporal distribution of rainfall and harvesting periods within a region. In addition, variations in total numbers of sediment yield events contributing to annual sediment yield across regions are attributed to differences in spatial distribution of rainfall, differences in ratoon lengths and differences in harvesting periods. On average, 51, 44, 30 and 52 events of sediment yield per year were simulated in the North Coast, South Coast, Zululand and Irrigated and Midlands regions respectively. Similarly, the frequency of occurrence of individual sediment yield events varies regionally and across regions as shown in Figure 6.2 and the reason for the differences is attributed to differences in temporal and spatial distribution of rainfall, differences in ratoon lengths and differences in harvesting periods.

An analysis of annual sediment yield summed from individual sediment yield events shows differences in magnitudes of sediment yield both annually and across regions as shown in Figure 6.3. Furthermore, the long term average sediment yield exceeds most of the annual sediment yield in each region as shown in Figure 6.3. Differences in annual magnitudes on a regional basis are attributed to variations in temporal distribution of rainfall and harvesting periods within a region. On the other hand, variations in annual sediment yield across regions are attributed to differences in spatial distribution of rainfall, differences in ratoon lengths and differences in harvesting periods. Similarly, the frequency of occurrence of annual sediment yield varies regionally and across regions as shown in Figure 6.4 and the reason for the differences is attributed to differences in temporal and spatial distribution of rainfall, differences in ratoon lengths and differences in harvesting periods.

Investigations of the five largest (0.2%) sediment yield events in each region show that each event constitutes a significant percentage towards the annual sediment yield as shown in Table 6.2. For example, the sediment yield event which occurred on 13/05/1971 in the North Coast contributed 83% of total sediment yield simulated in 1971. This event was triggered by a rainfall depth of 293 mm and coincided with the bare fallow period just before the next sugarcane replant and this is when the soil is most susceptible to erosion. Generally, the five largest events in the North Coast, South Coast, Zululand and Irrigated and Midlands regions contributed 21 – 89%, 66 – 89%, 28 – 83% and 29 – 95% to the annual sediment yield respectively.

In addition, the five largest events contributed 35%, 43%, 38% and 19% of the total simulated sediment yield for the whole period (*i.e.* 68 years) in the North Coast, South Coast, Zululand and Irrigated and Midlands regions respectively. The trends exhibited are logical because high rainfall events were received on days when the land surfaces were either under bare fallow or just after sugarcane was harvested.

The above observations are in agreement with Schulze *et al.* (2011) who noted that most erosion occurs in relatively few events. Therefore, design of soil and water conservation structures should be based on the few sediment yield events.

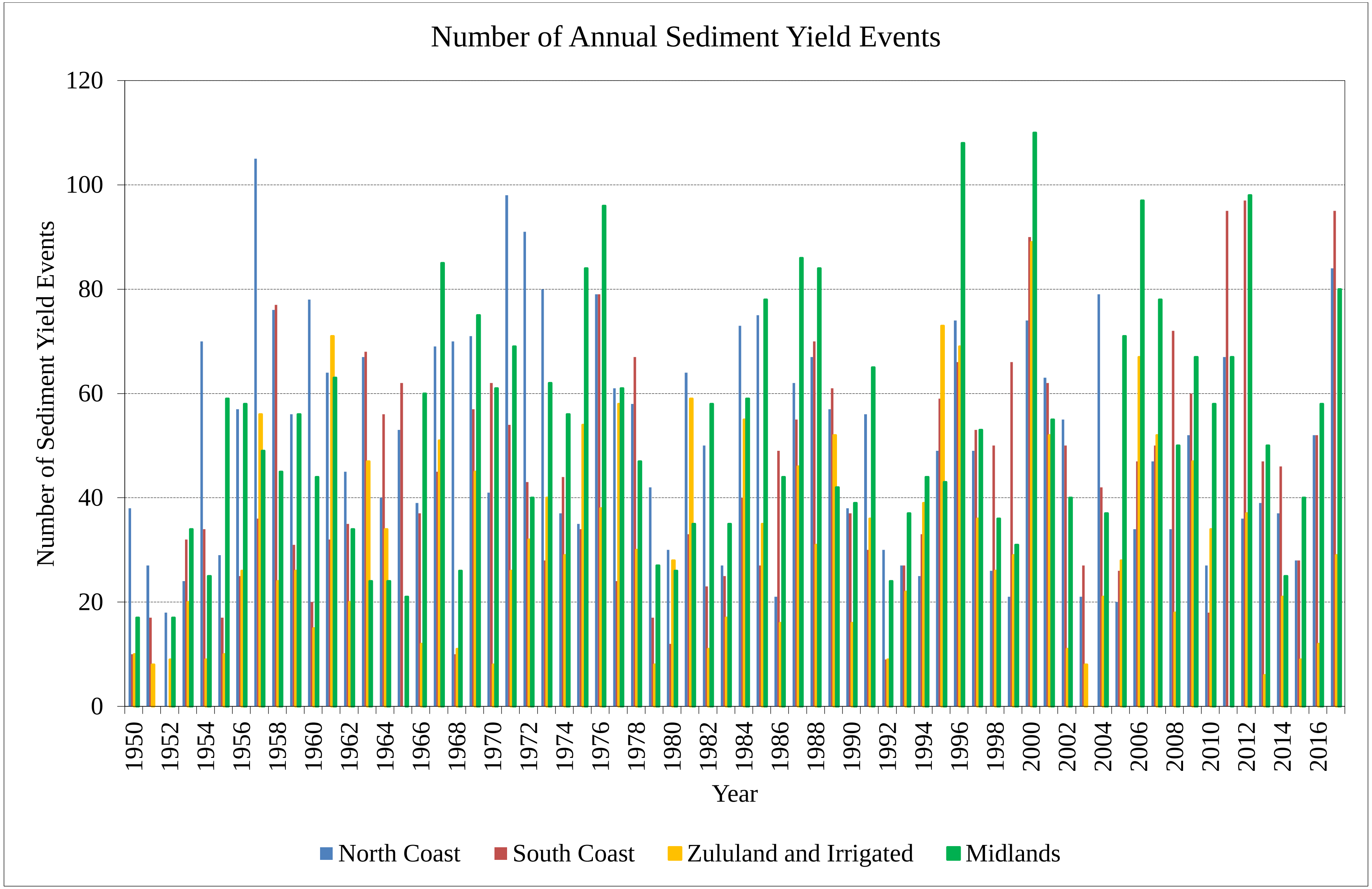

Figure 6.1 Number of sediment yield events on an annual basis

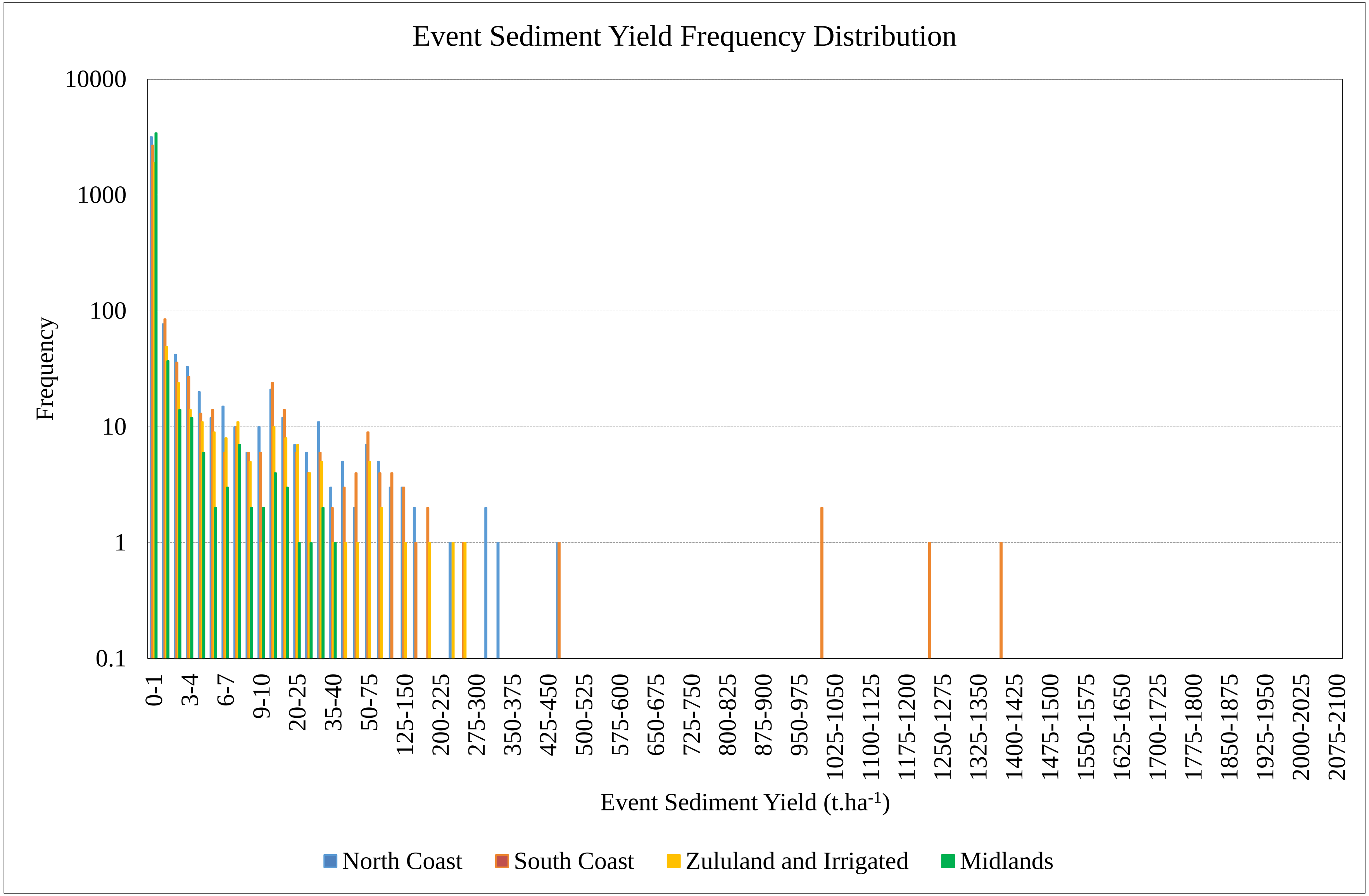

Figure 6.2 Event sediment yield distribution in the four homogenous climatic zones

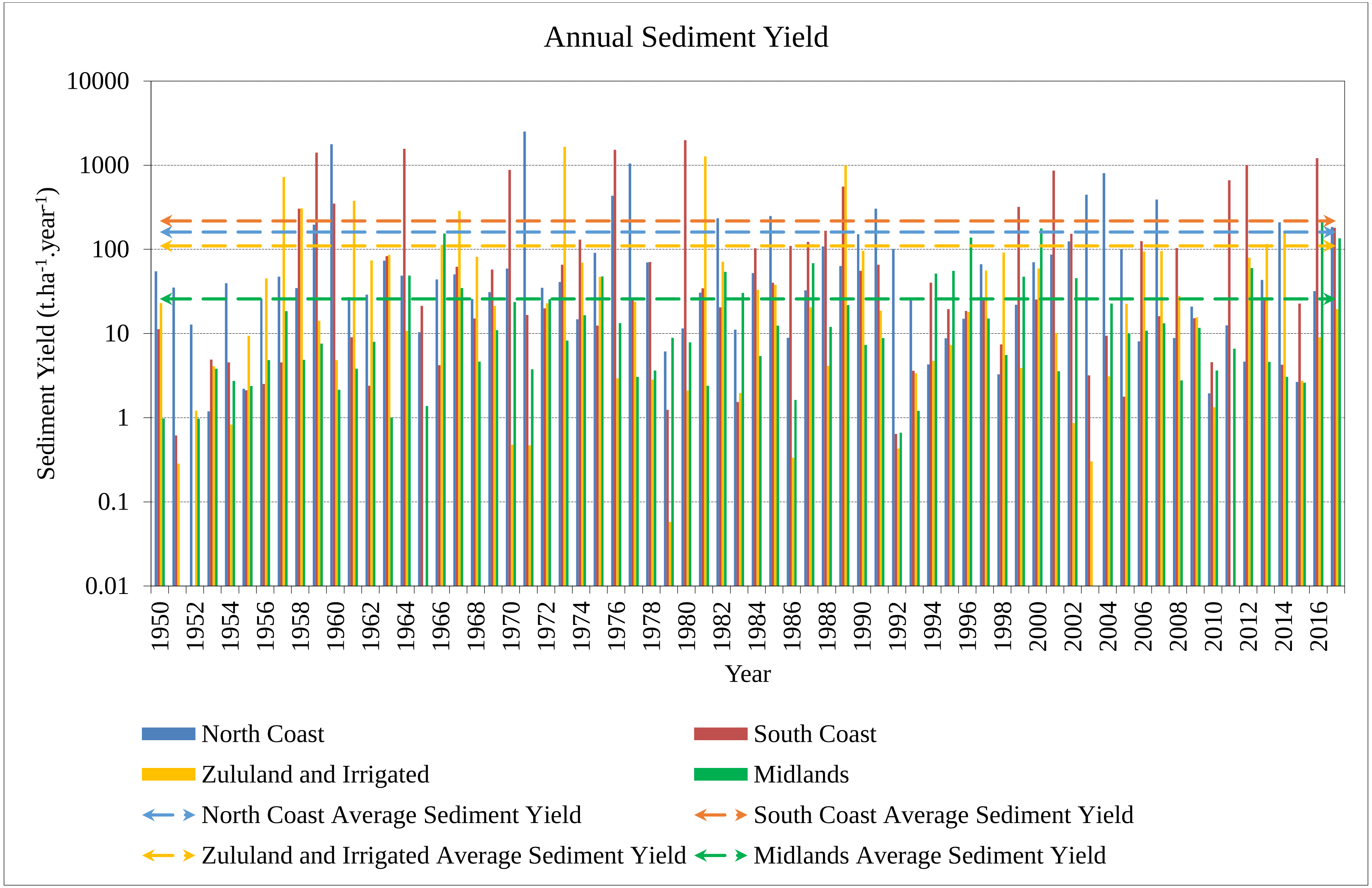

Figure 6.3 Sediment yield summed from individual events on an annual basis

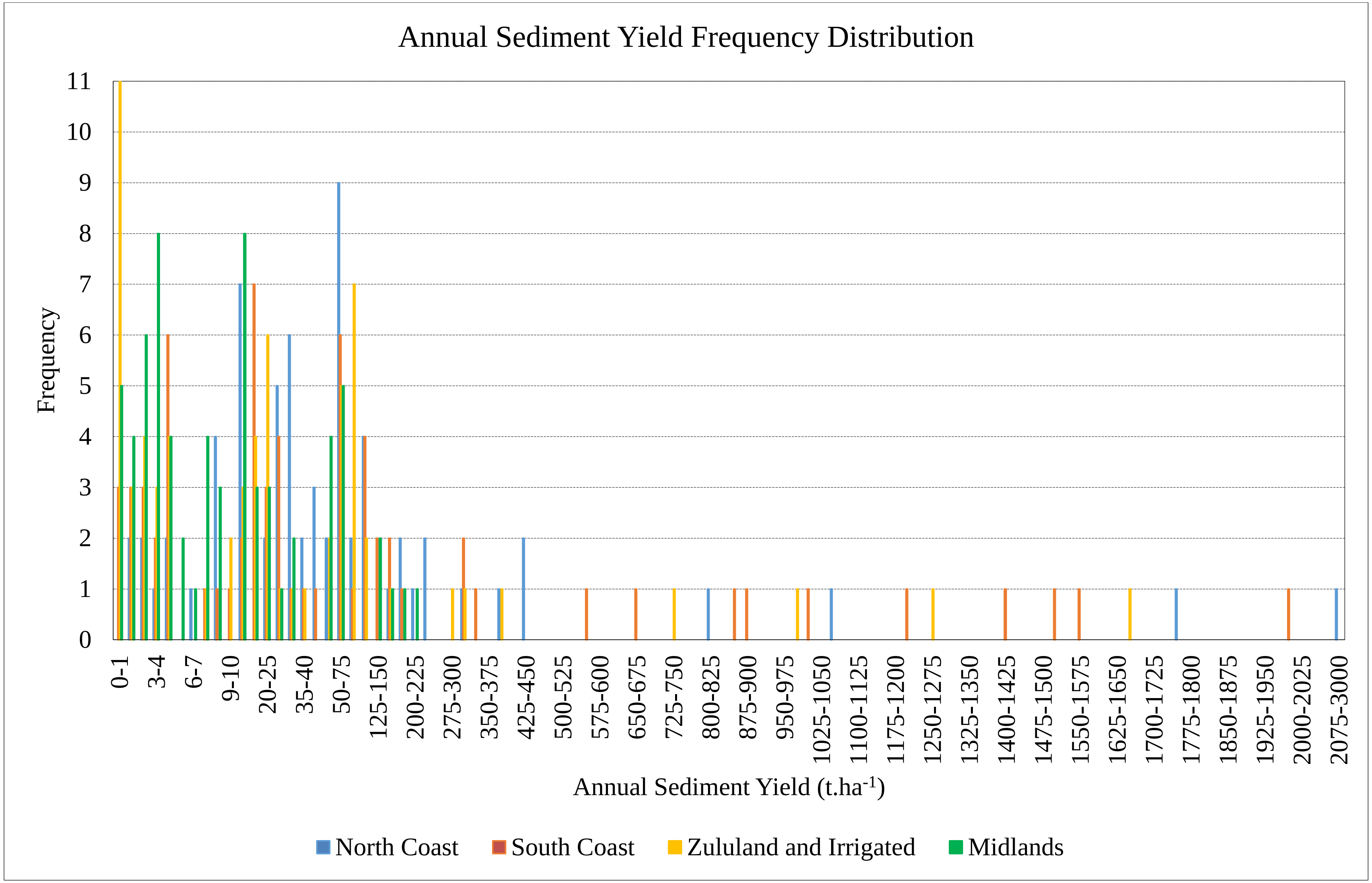

Figure 6.4 Annual sediment yield distribution in the four homogenous climatic regions

Table 6.2 Top five (0.2%) sediment yield events in the four regions

Region	Date	Rainfall (mm)	Runoff (mm)	Peak discharge ($m^3.s^{-1}$)	Event sediment yield ($t.ha^{-1}$)	Individual contribution to annual sediment yield (%)	Cumulative contribution to total sediment yield (%)	Management Practice
North Coast	13/05/1971	293.00	178.03	9.03	2078	83	35	Bare fallow period after last ratoon and before replant
	30/12/1960	122.50	56.78	2.55	503	28		Bare fallow period after last ratoon and before replant
	07/02/1977	151.50	75.30	3.71	466	44		Harvested
	14/04/2003	123.60	41.46	1.97	395	89		Bare fallow period after last ratoon and before replant
	09/11/1960	113.00	39.18	1.87	372	21		Harvested
South Coast	07/09/1980	257.90	130.17	8.49	1703	86	43	Bare fallow period after last ratoon and before replant
	20/06/1964	310.90	171.62	11.26	1396	89		Harvested
	18/05/1959	271.70	152.97	10.03	1227	87		Harvested
	25/07/2016	215.00	130.24	8.54	1024	84		Harvested
	20/03/1976	212.70	136.80	8.51	1008	66		Harvested
Zululand and Irrigated	29/09/1973	177.30	97.61	7.69	1373	83	38	Bare fallow period after last ratoon and before replant
	17/05/1981	99.00	35.83	2.67	431	34		Bare fallow period after last ratoon and before replant
	11/09/1981	111.60	34.43	2.49	405	32		Bare fallow period after last ratoon and before replant
	30/11/1989	81.20	31.71	2.33	382	38		Bare fallow period after last ratoon and before replant
	29/11/1989	74.20	24.44	1.77	282	28		Bare fallow period after last ratoon and before replant
Midlands	11/11/2016	50.00	13.31	1.26	103	46	19	Bare fallow period after last ratoon and before replant
	21/02/1966	54.90	10.65	0.96	78	51		Bare fallow period after last ratoon and before replant
	20/08/2016	54.00	9.21	0.81	65	29		Bare fallow period after last ratoon and before replant
	03/04/2000	38.00	6.42	0.55	43	95		Bare fallow period after last ratoon and before replant
	26/10/1999	41.80	6.32	0.54	42	88		Bare fallow period after last ratoon and before replant

6.3.2 Relationships between extreme events of sediment yield and the rainfall, runoff and peak discharge events associated with them

A summary of extreme events of sediment yield for the 10, 20, 25 and 50 year return periods in the four regions and the rainfall, runoff and peak discharge events associated with them are shown in Table 6.3. From Table 6.3, it is evident that the most extreme sediment yield is not necessarily caused by the most extreme rainfall, runoff and peak discharge events. This is attributed to the variations in crop cover at different stages of sugarcane growth which impact on the sediment yield. For example, a rainfall event in the North Coast which occurred on 22/01/1971 with a 14.8 year return period generated runoff, peak discharge and sediment yield events of 5.0, 1.3 and 25.0 year return periods respectively. This event coincided with the bare fallow period just before the next sugarcane replant and this is when the soil is most susceptible to erosion.

Similarly, in the South Coast, Zululand and Irrigated regions and Midlands, rainfall return periods of 26.2, 9.1 and 3.5 years respectively resulted in sediment yield events with higher return periods as shown in Table 6.3. However, when simulations were conducted for the same scenarios but with green manuring practices after the last ratoon crop and before replant as opposed to bare fallow conditions, the sediment yield drastically reduced as shown in Table 6.4 and rainfall events of higher return periods generated runoff of lower return periods. Therefore, designs should be conducted for bare fallow conditions which represent conditions when soils are most susceptible to erosion. In addition, rainfall events of higher return periods generated runoff and peak discharge events of lower return periods. This is attributed to variations in antecedent soil moisture conditions which impact on the runoff and peak discharge generated.

From a sediment yield perspective, any return period for rainfall, runoff and peak discharge would result in high sediment yield as long as the soil surface is not adequately protected. As described in Chapter 5, different management practices were recommended so as to maintain sediment yield within tolerable limits of 5 $t.ha^{-1}.year^{-1}$. Therefore, return periods corresponding to 5 $t.ha^{-1}$ were calculated using Equation 6.1 and compared with same day return periods for rainfall, runoff and peak discharge, as shown in Table 6.5. From Table 6.5, it is generally evident that higher return period rainfall events generate runoff and peak discharge events of lower return periods and sediment yield events of higher return periods. This is attributed to variations in antecedent moisture conditions which impact on the runoff and peak discharge generated and variations in crop cover at different stages of sugarcane growth which impact on the sediment yield. Therefore, to limit sediment yield to 5 $t.ha^{-1}$, rainfall return periods were used as the control point and rounded to the nearest multiple of 10 to obtain the recommended design return period as shown in Table 6.5.

Table 6.3 Extreme events of sediment yield and the rainfall, runoff and peak discharge events associated with them in the four regions for a “no structure, conventional tillage, no green manuring, burnt, re-burnt harvesting practice and 40% slope” scenario

Region	Date	Sediment yield ($t.ha^{-1}$)	Sediment yield return period (Year)	Rainfall (mm)	Rainfall return period (Year)	Runoff (mm)	Runoff return period (Year)	Peak discharge ($m^3.s^{-1}$)	Peak discharge return period (Year)	Management Practice
North Coast	14/03/2000	1.09	10.0	58.0	47.6	9.5	24.4	0.32	3.1	Fifth month after harvesting (canopy not fully established)
	03/03/1988	5.24	20.0	62.9	55.6	16.0	45.7	0.60	5.0	Fourth month after harvesting (canopy not fully established)
	22/01/1971	7.49	25.0	31.5	14.8	3.4	5.0	0.07	1.3	Bare fallow period after last ratoon and before replant
	11/09/1958	22.63	50.0	61.0	52.6	6.3	13.9	0.22	2.6	Harvested
South Coast	26/02/1988	1.26	10.0	29.0	10.0	8.2	19.0	0.14	1.6	Third month after harvesting (canopy not fully established)
	18/01/1986	6.54	20.0	125.4	*	57.7	*	3.59	30.3	Fully established canopy
	01/03/1997	9.69	25.0	63.6	41.7	11.9	31.0	0.59	3.8	Second month after harvesting (canopy not fully established)
	25/08/1970	29.82	50.0	51.6	26.2	4.8	9.4	0.19	1.9	Bare fallow period after last ratoon and before replant
Zululand and Irrigated	13/11/1953	1.10	10.0	61.5	42.6	11.7	22.0	0.74	5.8	Fully established canopy
	02/08/2009	5.86	20.0	45.0	18.2	2.0	2.2	0.07	1.3	Harvested
	14/09/1981	8.38	25.0	31.0	9.1	2.1	2.3	0.06	1.2	Bare fallow period after last ratoon and before replant
	14/03/2000	29.95	50.0	300.0	*	201.3	*	15.62	*	Fully established canopy
Midlands	27/02/1956	0.33	10.0	7.8	3.5	3.8	7.4	0.32	2.7	Fully established canopy
	20/03/1976	1.27	20.0	41.7	57.1	18.4	64.9	1.55	14.9	Fully established canopy
	25/09/1954	1.88	25.0	86.9	*	22.7	*	2.16	31.3	Fully established canopy
	15/12/2012	5.81	50.0	44.0	71.4	9.2	21.5	0.75	5.5	Third month after harvesting (canopy not fully established)

* Return period value exceeds length of data duration

Table 6.4 Sediment yield and the rainfall, runoff and peak discharge events associated with them in the four regions for a "no structure, conventional tillage, green manuring, burnt, re-burnt harvesting practice and 40% slope" scenario

Region	Date	Sediment yield ($t.ha^{-1}$)	Sediment yield return period (Year)	Rainfall (mm)	Rainfall return period (Year)	Runoff (mm)	Runoff return period (Year)	Peak discharge ($m^3.s^{-1}$)	Peak discharge return period (Year)	Management Practice
North Coast	22/01/1971	0.69	9.5	31.5	14.8	3.0	3.7	0.06	1.3	Green manuring period after last ratoon and before replant
South Coast	25/08/1970	4.19	20.9	51.6	26.2	4.6	7.1	0.19	1.9	Green manuring period after last ratoon and before replant
Zululand and Irrigated	14/09/1981	0.61	8.9	31.0	9.1	1.9	2.0	0.05	1.2	Green manuring period after last ratoon and before replant
Midlands	15/12/2012	3.7	50.0	44.0	71.4	5.2	19.2	0.31	2.6	Third month after harvesting (canopy not fully established)

Table 6.5 5 $t.ha^{-1}$ sediment yield events simulated for a "no structure, conventional tillage, no green manuring, burnt, re-burnt harvesting practice and 40% slope" scenario and the rainfall, runoff and peak discharge events associated with them in the four regions

Region	Date	Sediment yield ($t.ha^{-1}$)	Sediment yield return period (Year)	Rainfall (mm)	Rainfall return period (Year)	Runoff (mm)	Runoff return period (Year)	Peak discharge ($m^3.s^{-1}$)	Peak discharge return period (Year)	Rainfall preceding event (mm)	Period preceding event (day)	Management practice	Recommended return period (Year)
North Coast	29/05/1971	5	19.61	30.7	14.08	4.2	7.41	0.07	1.33	11.0	7	Bare fallow period after last ratoon and before replant	20
South Coast	05/12/1970	5	17.54	41.3	17.33	3.5	5.71	0.11	1.43	29.4	7	Second month after replant (canopy not fully established)	20
Zululand and Irrigated	09/03/1963	5	18.18	4.9	1.18	1.7	1.75	0.07	1.28	88.0	1	Second month after harvesting (canopy not fully established)	10
Midlands	10/04/2017	5	48.97	28.0	20.00	1.5	1.75	0.07	1.02	7.0	7	Bare fallow period after last ratoon and before replant	20

6.3.3 Economic impact of varying design return periods across different homogenous climatic zones

Plots of the economic impact of varying design return periods from the minimum recommended 10 year design return period to the newly recommended 20 year design return period across the four homogenous climatic zones in the sugar industry of South Africa are shown in Figure 6.5. The summary of designed sections and their costs are shown in Table 6.6.

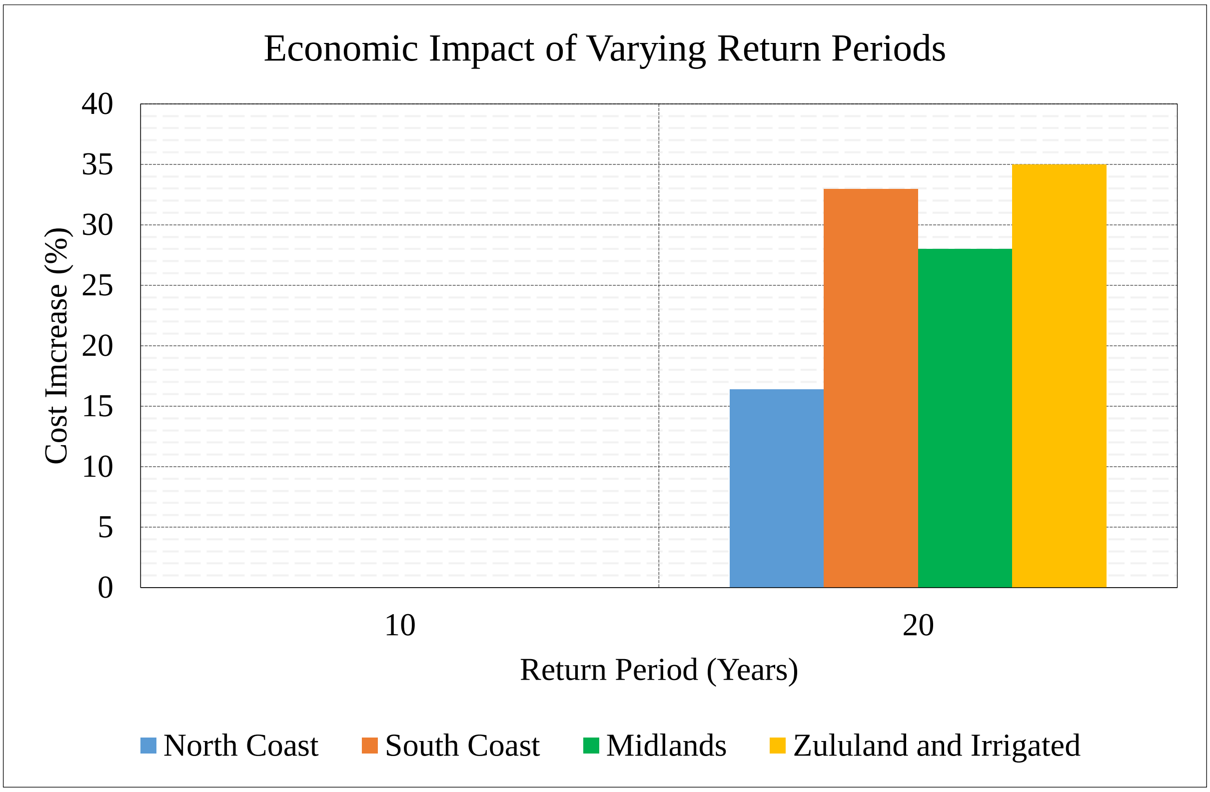

Figure 6.5 Economic impact of varying return periods

The cost increase in the variation of design return period from 10 years to 20 years is 16%, 33%, 28% and 35% in the North Coast, South Coast, Midlands and Zululand and Irrigated regions respectively, as shown in Figure 6.5. It is also evident that the increases in costs in the South Coast, Midlands and Zululand and Irrigated regions are similar while the cost increases in the North Coast is approximately 50% of cost increases in the South Coast region. This is because North Coast receives much more rainfall than the other regions implying that the catchment lag times in the North Coast are much greater than the catchment lag times in the other regions as shown in Appendix 5.3. Catchment lag time is related to mean annual precipitation, hence the greater the precipitation, the greater the catchment lag time (Schmidt and Schulze, 1984). On the other hand, catchment lag time is inversely proportional to peak discharge, and the greater the catchment lag time, the lesser the peak discharge and vice versa. In addition, the greater the peak discharge, the greater the size of the designed section which further increases the costs.

The general variations in cost increases are attributed to the regional differences in climate and ratoon lengths of sugarcane all which impact on runoff and peak discharge generated, thereby increasing the size of the soil and water conservation structures that have to be excavated. Increase in cost is a function of the size of soil and water conservation structure that has to be excavated and the bigger the section, the more expensive it becomes. Considering that erosion has negative impacts on sustainable crop production and increases the costs of replanting washed away crops, it is worth adopting the 20 year return period in the design of soil and water conservation structures. This is because using the 20 year return period in the design of soil and water conservation structures will ensure that sediment yield is maintained within sustainable limits of 5 $t.ha^{-1}$.

Table 6.6 Hydraulic sections and design implementation costs of soil and water conservation structures in the four homogenous climatic zones in the sugar industry of South Africa

Region	Return period (year)	Design discharge ($m^3.s^{-1}$)	Hydraulic mean depth (m)	Top width (m)	Area (m^2)	Hydraulic radius (m)	Flow velocity ($m.s^{-1}$)	Cost (R)	Cost increase from 10 year return period cross-sectional area (%)
North Coast	10	1.2	0.75	5.50	2.8	0.48	0.50	6116	0
	20	1.9	0.80	6.00	3.2	0.51	0.60	7117	16
South Coast	10	1.6	0.80	5.50	2.9	0.50	0.57	6524	0
	20	2.7	0.90	6.50	3.9	0.57	0.74	8674	33
Zululand and Irrigated	10	1.5	0.80	5.00	2.7	0.50	0.57	5931	0
	20	2.5	0.90	6.00	3.6	0.57	0.74	8006	35
Midlands	10	1.1	0.75	5.00	2.5	0.47	0.47	5560	0
	20	1.7	0.80	6.00	3.2	0.51	0.58	7117	28

6.4 Discussion and Conclusions

The total number and magnitudes of sediment yield events contributing to annual sediment yield vary annually and across regions. The variations within a given region were attributed to variations in temporal distribution of rainfall and harvesting periods, whereas variations across regions were attributed to differences in spatial distribution of rainfall, differences in ratoon lengths and differences in harvesting periods. In addition, very few events (*i.e.* 0.2%) constituted significant percentages (*i.e.* 21 – 95%) towards the annual sediment yield, and 0.2% of the sediment yield events in each region constituted 35%, 43%, 38% and 19% of the total simulated sediment yield in the North Coast, South Coast, Zululand and Irrigated and Midlands regions respectively. Therefore, design of soil and water conservation structures should be based on the few sediment yield events which contribute to annual erosion.

In general, extreme sediment yield events are not necessarily caused by extreme rainfall, runoff and peak discharge events, as the variations in crop cover at different stages of sugarcane growth play a major role in the sediment yield generated. However, when simulations were conducted for the same scenarios but with green manuring practices after the last ratoon crop and before replant as opposed to bare fallow conditions, the sediment yield drastically reduced and rainfall events of higher return periods generated runoff of lower return periods. With sediment yield maintained within tolerable limits of 5 $t.ha^{-1}.year^{-1}$, rainfall events generally generated runoff and peak discharge events of lower return periods than the rainfall return periods, and sediment yield events of higher return periods than the rainfall return periods. Therefore, to limit sediment yield to sustainable amounts of 5 $t.ha^{-1}$, return periods of rainfall events generating the 5 $t.ha^{-1}$, were used as the control point and rounded to the nearest multiple of 10 to obtain the recommended design return period. The 20 year return period is thus the recommended design return period for soil and water conservation structures and the cost implication in variation of design return periods from the minimum 10 year return period to the 20 year return period was 16%, 33%, 28% and 35% for the North Coast, South Coast, Midlands and Zululand and Irrigated regions respectively. Considering that soil erosion is associated with adverse effects on sustainable crop production and also increases costs of replanting destroyed crops, it is recommended that the 20 year return period is adopted in the design of soil and water conservation structures in the sugar industry in South Africa. In addition, designs should be conducted for bare fallow conditions which represent conditions when soils are most susceptible to erosion. Finally, considering that the simulations used in this study are for one historical rainfall sequence and fixed planting dates, there is need to conduct iterative runs for different planting dates and perhaps using stochastic climates as input.

6.5 Acknowledgements

I am highly indebted to the South African Sugarcane Research Institute (SASRI) for funding this research and Dr Peter Tweddle for the guidance in costing the construction of soil and water conservation structures.

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7 IMPACTS OF SOIL AND WATER CONSERVATION STRUCTURES ON STREAM FLOW REDUCTION IN THE SUGAR INDUSTRY OF SOUTH AFRICA

This Chapter is under review in *Water SA.*

Otim, D, Smithers, JC, Senzanje, A and van Antwerpen, R. "In press". Impacts of soil and water conservation structures on stream flow reduction in the sugar industry of South Africa. *Water SA* "In press".

Abstract

Soil conservation seeks to avoid and moderate soil loss through erosion and also to promote increased infiltration of rainfall into the soil, thereby slowing down and reducing the amount of runoff. Numerous soil conservation practices are in existence and they include mechanical structures, soil management practices and agronomic measures. In South Africa, contour banks and spill-over roads are the soil and water conservation structures generally employed in the protection of croplands against erosion in the sugar industry. Stream Flow Reduction (SFR) is the decrease in runoff as a consequence of anthropogenic activities, and this is influenced by the spatial distribution and infiltration properties of soils, hydraulic characteristics and extent of aquifers, the rate, frequency and amount of recharge, evapotranspiration rates, distribution of vegetation types, topography and climate. The Conservation of Agricultural Resources Act 43 of 1983 governs soil and water conservation practices in South Africa. The objective of this study was to investigate the impacts of soil and water conservation structures on stream flow reduction in the sugar industry of South Africa. The study area consists of sugarcane growing areas in South Africa (*i.e.* South Coast, North Coast, Zululand and Irrigated, and Midlands) and is described in Chapter 5. The data and results of runoff simulated with the Agricultural Catchments Research Unit (*ACRU*) model for the four homogenous climatic zones in the sugar industry of South Africa was utilised together with assumptions which are also presented in Chapter 5. Comparisons of simulated runoff against time across the different homogenous climatic zones were made to determine how runoff varies across each region. In addition, impacts of soil and water conservation structures on SFR were assessed by comparing the difference between mean annual stream flows from scenarios where sugarcane was grown on fields with soil and water conservation structures and those where sugarcane was grown on fields without soil and water conservation structures, with negative values denoting SFR. On the other hand, positive values would denote increases in stream flow. The results showed that SFR was greater in clayey soils than sandier soils because clayey soils have higher water holding capacities than sandier soils. Furthermore, the Zululand and Irrigated region registered the greatest SFR followed by the Midlands, North Coast and South Coast regions. Regional differences in SFR were attributed to variations in evapotranspiration rates and climate in the homogenous regions. In conclusion, soil and water conservation structures result in decreases in simulated stream flow across all regions, soil types and practices. This was due to the fact that soil and water conservation structures intercept runoff and increase the amount of water infiltrating into the soil, thereby slowing down and reducing the amount of runoff but runoff flows quicker once in a waterway. However, the SFR caused by soil and water conservation structures is insignificant (*i.e.* < 5.5%) and would not likely necessitate their declaration as SFRAs as contained in the National Water Act of South Africa. This is because, for an activity to be declared as a SFRA, its impact on SFR should be greater than 10% of Mean Annual Runoff. However, if soil and water conservation structures were to be eliminated, SFR would decrease although soil erosion would increase which is undesirable and will contribute to unsustainable long term production.

Keywords: soil and water conservation, South Africa, stream flow reduction, sugarcane

7.1 Introduction

Plant growth, agricultural yields and water quality are adversely hindered by soil erosion (Issaka and Ashraf, 2017). Poor land management, which causes damage to soil thereby leading to water runoff across a landscape instead of adequate infiltration is among the factors that cause erosion (Liu, 2016). Soil conservation is the avoidance and moderation of soil lost through erosion (Sustainet, 2010). The purpose of soil conservation is to maintain the rate of soil loss at levels lower than soil formation rates (Morgan, 2005). In addition, soil conservation ensures increases in the amount of water infiltrating into the soil, hence slowing down and reducing the amount of water running off (Sustainet, 2010). Many soil conservation practices are in existence and range from mechanical structures (*e.g.* contour bunds, terraces, check dams), soil management practices and agronomic measures (*e.g.* cover crops, tillage, mulching, vegetation strips, re- vegetation, and agroforestry) (Krois and Schulte, 2014). According to SASA (2002), waterways, contour banks and spill-over roads are soil and water conservation structures employed in the protection of cropland against erosion in the sugar industry of South Africa. Contour banks are constructed across a slope in order to intercept runoff water (Matthee and Van Schalkwyk, 1984) and safely discharge it into stable grassed waterways or natural drains (Carey *et al.*, 2015). Spill-over roads on the other hand allow runoff to flow from a higher field across the road structure to a lower field (SASA, 2002). Besides the positive effect of soil and water conservation measures on hydrology, they increase infiltration and lower runoff thereby leading to lower soil loss rates (Nyssen *et al.*, 2009). Generally, catchment runoff response from rainfall events depends on interactions between rainfall amount and intensity, antecedent soil moisture conditions and land cover (Maher, 2000).

In South Africa, soil and water conservation practices are governed by the Conservation of Agricultural Resources Act (CARA) 43 of 1983 and states that "The objectives of this Act are to provide for the conservation of the natural agricultural resources of the Republic by the maintenance of the production potential of land, by the combating and prevention of erosion and weakening or destruction of the water sources, and by the protection of the vegetation and the combating of weeds and invader plants" (CARA, 1983).

Article 6 "Control measures", gives guidance to land users on soil and water conservation practices in South Africa as illustrated below:

(a) the utilization and protection of land which is cultivated,
(b) the prevention or control of waterlogging or salination of land,
(c) the regulating of the flow pattern of runoff water,
(d) the restoration or reclamation of eroded land or land which is otherwise disturbed or denuded,
(e) the protection of water sources against pollution on account of farming practices, and
(f) the construction, maintenance, alteration or removal of soil conservation works or other structures on land.

Stream Flow Reduction (SFR) is the decrease in various aspects of the overall flow regime (Smakhtin, 2001). According to NWA (1998), commercial forestry is the only currently declared Stream Flow Reduction Activity (SFRA) in South Africa but any activity including the cultivation of any particular crop may be declared as a SFRA if that activity is likely to reduce the availability of water in a water course. Intensive agriculture systems (*e.g.* semipermanent and permanent cash cropping, and monoculture plantations) are associated with negative impacts like changes in stream flow response and increased surface erosion (Ziegler *et al.*, 2009). According to Bruijnzeel (2004), the net impact on the amount and timing of stream discharge associated with forest conversion to agriculture is a combination of evapotranspiration and soil infiltration. The impact of sugarcane on water resources is likely to be negligible in both the North Coast and South Coast whereas in the Midlands, it is possible that sugarcane has significant impacts on available water resources (Jewitt *et al.*, 2009). Therefore, consideration should be given to the regulation of sugarcane as a SFRA. For an activity to be considered for declaration as a SFRA, its impact should be significant (*i.e.* impact ≥ 10% of Mean Annual Runoff (MAR)) and the geographic extent should be significant too (*i.e.* area ≥ 10% of quaternary catchment under consideration) (Jewitt *et al.*, 2009). Factors which influence SFR include spatial distribution and infiltration properties of soils, hydraulic characteristics and extent of aquifers, the rate, frequency and amount of recharge, evapotranspiration rates, distribution of vegetation types, topography and climate (Smakhtin, 2001). In general, evapotranspiration rate increases non-linearly with in rainfall (Zhang *et al.*, 1999). Quantification of SFR involves comparison of stream flows associated with a given activity against baseline stream flows (Jewitt *et al.*, 2009). Hence, the objective of this paper was to investigate the impacts of soil and water conservation structures on stream flow reduction in the sugar industry of South Africa. It is important to note that the stream flow reduction of growing sugarcane compared to a natural vegetation will not be considered.

7.2 Methods and Assumptions

This investigation utilised data and results of runoff simulated with the Agricultural Catchments Research Unit (*ACRU*) model from a hypothetical 1 km^2 catchment for the four homogenous climatic zones (*i.e.* South Coast, North Coast, Zululand and Irrigated and Midlands) in the sugar industry of South Africa. The study area, methodology and assumptions of which are presented in Chapter 5. The mean annual rainfall for the South Coast, North Coast, Zululand and Irrigated, and Midlands are 934, 1 146, 642 and 818 mm respectively. Over 46 080 scenarios were simulated for the period 1950 – 2017 (*i.e.* 68 years) as shown in Chapter 5 but for purposes of this study, only a few select scenarios were used in the analysis of relationships.

7.2.1 Impacts of soil and water conservation structures on stream flow reductions in the sugar industry

In order to assess impacts of soil and water conservation structures on Stream Flow Reductions (SFRs), the simulated scenarios were summarised into two broad scenarios. For Scenario 1, it was assumed that sugarcane was grown on fields without soil and water conservation structures (*i.e.* baseline activity) and while for Scenario 2, sugarcane was grown on fields containing soil and water conservation structures. The SFRs were estimated by subtracting the annual average flows from Scenario 1 from those of Scenario 2 and a negative value denotes a SFR. On the other hand, a positive value would denote an increase in stream flow. Plots of SFRs against each soil and water conservation practice for the various soil textural classes in the sugar industry were made and relationships analysed.

7.2.2 Relationships in stream flow reductions due to soil and water conservation structures across different homogenous climatic zones

In order to study relationships in SFRs due to soil and water conservation structures across different homogenous climatic zones, graphs showing relationships in SFRs due to soil and water conservation structures in sugarcane fields in the various homogenous regions were made. The relationships shown were assessed by comparing SFR percentages and conclusions drawn.

7.3 Results and Discussion

The results and discussions of the analysis of relationships in runoff across the different homogenous regions and assessment of the impacts of soil and water conservation structures on SFRs are presented below.

7.3.1 Impacts of soil and water conservation structures on stream flow reductions

Plots of SFRs against each soil and water conservation practice for the various soil textural classes in the sugar industry of South Africa for the North Coast are shown in Figure 7.1 and the discussion follows thereafter.

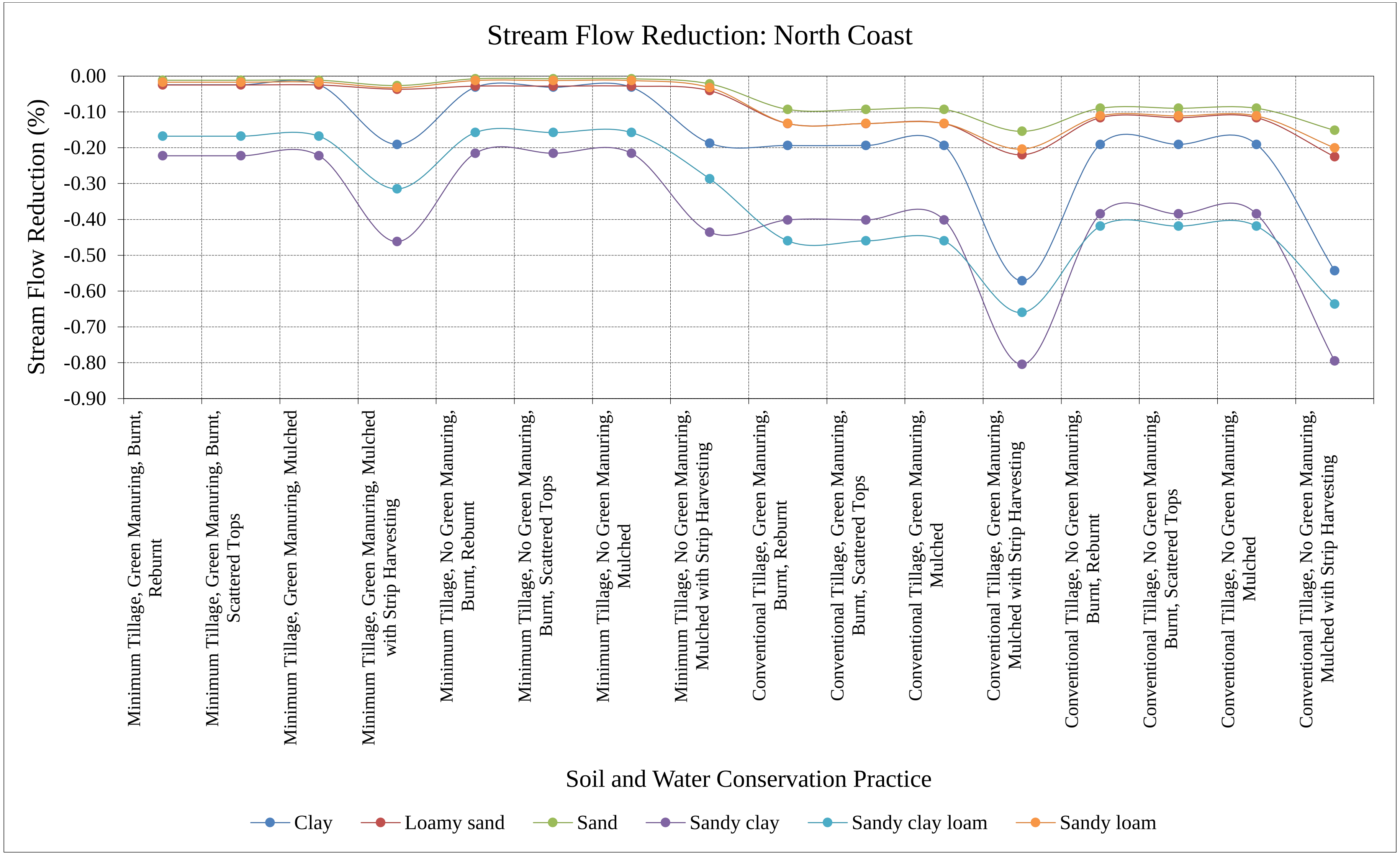

Figure 7.1 SFRs due to soil and water conservation structures in sugarcane fields in the North Coast region

SFR varies between 0.02% and 0.80% of the MAR from fields without soil and water conservation structures (*i.e.* baseline activity) in the North Coast with less SFR in the sandier soils than clayey soils as shown in Figure 7.1. The relationship exhibited is logical because clayey soils have higher water holding capacities than sandier soils. The SFRs for the South Coast, Midlands and Zululand and Irrigated regions are summarised in Table 7.1.

Table 7.1 Variation of SFRs as a percentage of MAR from baseline activities in the South Coast, Midlands, and Zululand and Irrigated regions

Region	SFR (%)
South Coast	0.00 – 0.42
Midlands	0.05 – 1.91
Zululand and Irrigated	0.28 – 5.36

The SFRs for the South Coast, Midlands, and Zululand and Irrigated regions also follow similar relationships as SFRs in the North Coast and the plots are shown in Figure 7.2 to Figure 7.4, while the mean annual stream flows and SFRs due to soil and water conservation structures in sugarcane fields are shown in Appendix 7.1.

Based on the above observations, it is evident that soil and water conservation structures cause decreases in stream flow (*i.e.* negative values) across all regions, soil types and practices with the greatest reduction occurring in the green manuring, mulched with strip harvesting practices. This is because the soil and water conservation structures intercept runoff and increase the amount of water infiltrating into the soil thereby slowing down and reducing the amount of water running off. According to Jewitt *et al.* (2009), activities whose impacts on SFR are greater than 10% of the MAR should be considered for declaration as SFRAs. Therefore, the impact of soil and water conservation structures on SFR is insignificant (*i.e.* < 5.5%) and does not necessitate the consideration of declaring soil and water conservation structures in sugar cane production as SFRAs as contained in the National Water Act of South Africa. In addition, soil and water conservation structures regulate the flow pattern of runoff and combat erosion which is a requirement of the Conservation of Agricultural Resources Act (CARA) 43 of 1983. Therefore, eliminating soil and water conservation structures would decrease SFR but increase soil erosion which is undesirable. The greatest reduction occurring in the green manuring, mulched with strip harvesting practices is because they intercept runoff and increase the amount of water infiltrating into the soil.

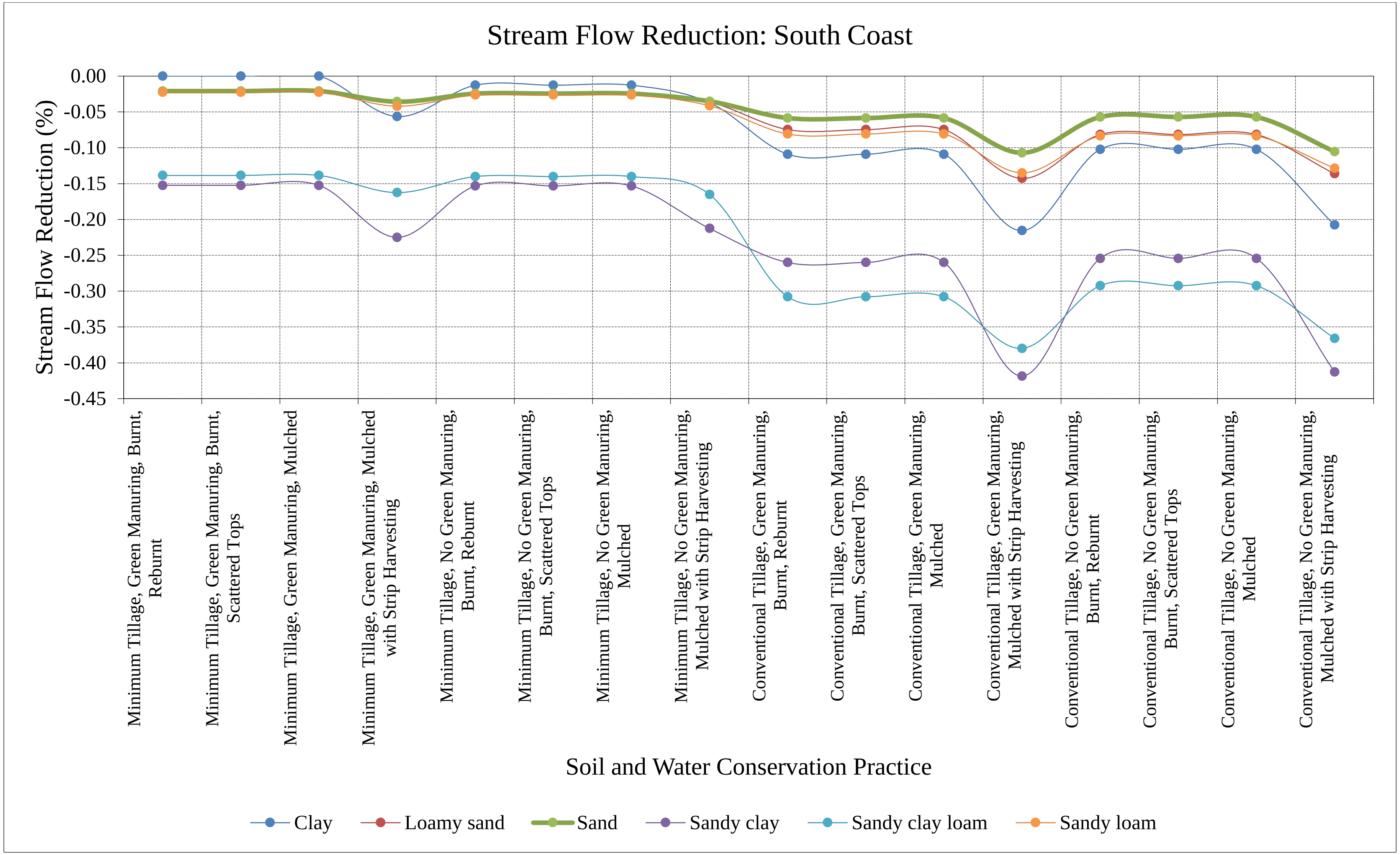

Figure 7.2 SFRs due to soil and water conservation structures in sugarcane fields in the South Coast region

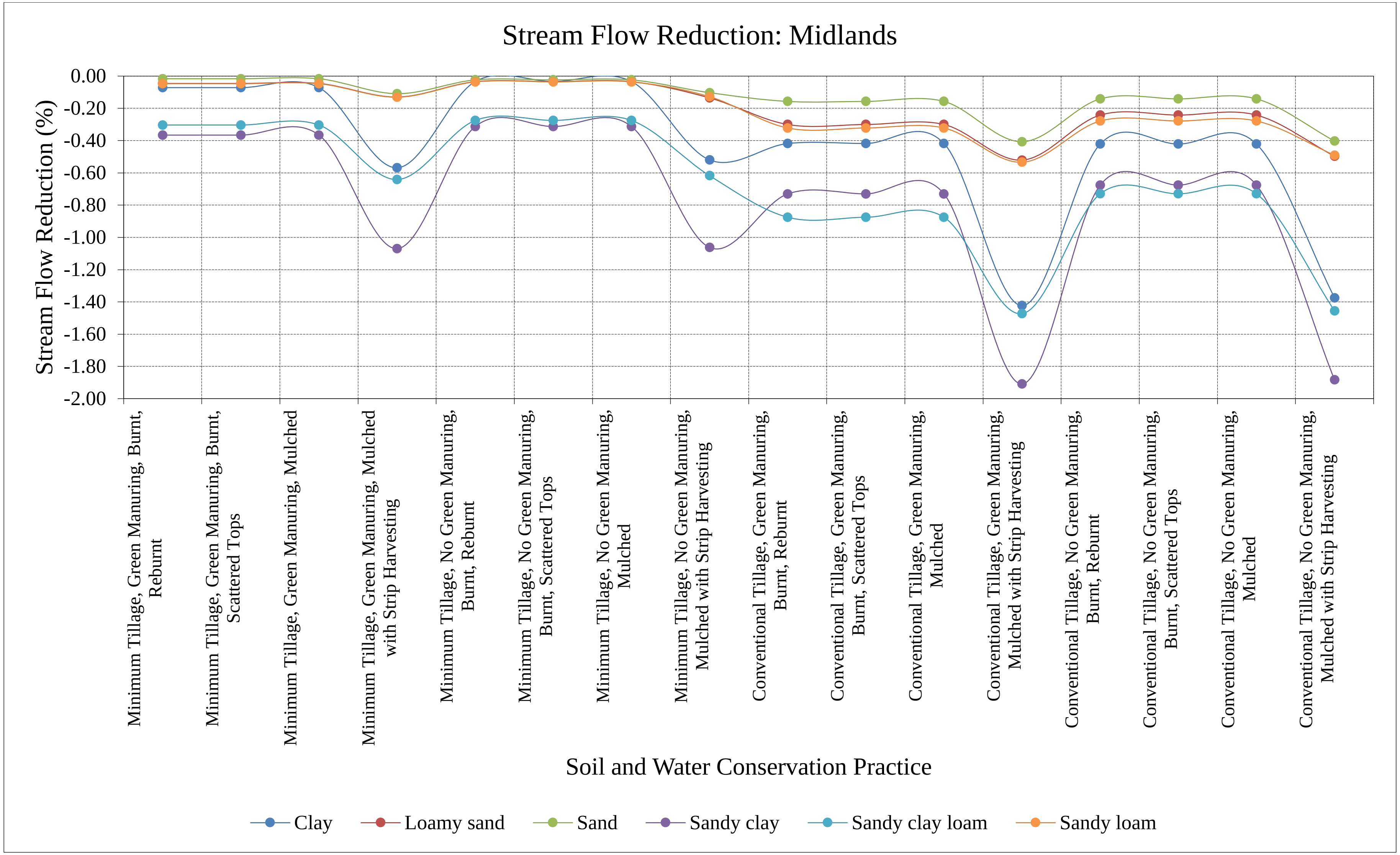

Figure 7.3 SFRs due to soil and water conservation structures in sugarcane fields in the Midlands region

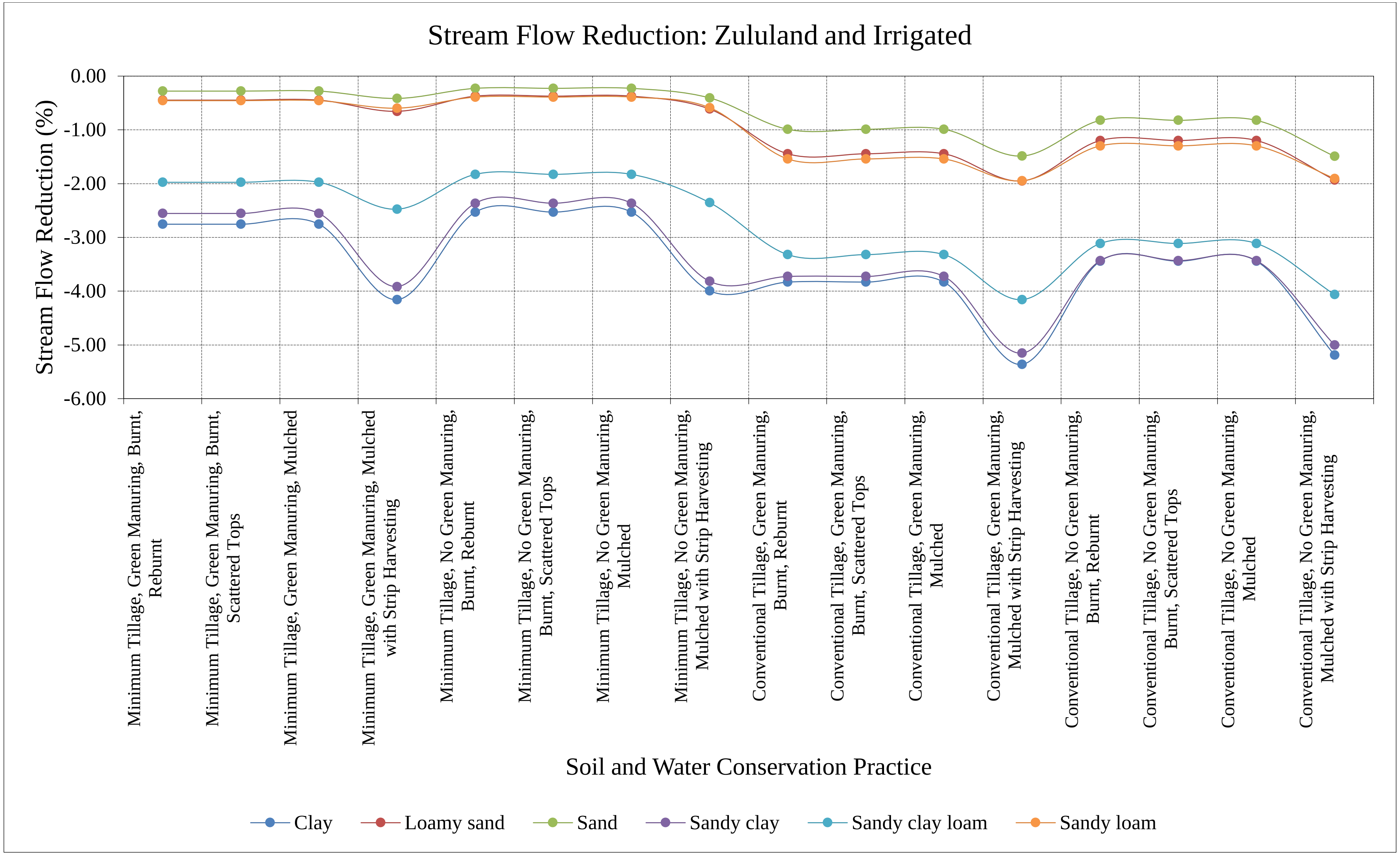

Figure 7.4 SFRs due to soil and water conservation structures in sugarcane fields in the Zululand and Irrigated region

7.3.2 Relationships in stream flow reductions due to soil and water conservation structures across different homogenous climatic zones

Graphs depicting relationships in SFRs due to soil and water conservation structures in sugarcane fields in the various homogenous regions are shown in Figure 7.5 and the discussion follows thereafter. The greatest SFR occurs in the Zululand and Irrigated region followed by the Midlands, North Coast and South Coast regions. The differences in magnitudes of SFRs in the regions is attributed to variations in evapotranspiration rates and climate in the homogenous regions. However, the differences in magnitudes of SFR are insignificant because they are all less than 10% of the MAR. The relationships exhibited are similar irrespective of the soil textural class with the only differences occurring in the magnitudes of SFR.

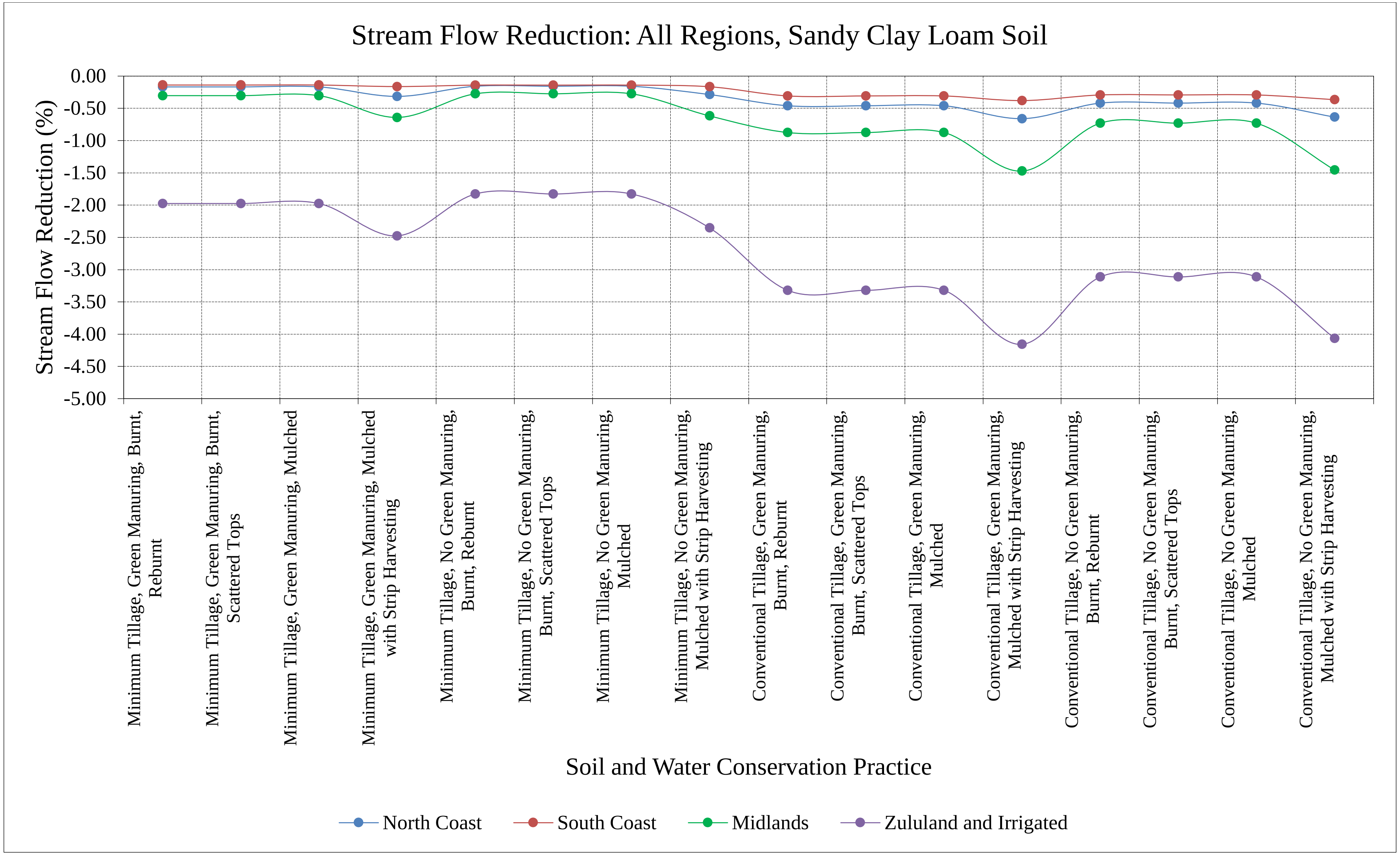

Figure 7.5 Relationships of SFRs due to soil and water conservation structures in sugarcane fields in the various homogenous regions

7.4 Conclusions

Generally, the impact of soil and water conservation on SFRs vary between 0.02% and 0.80% in the North Coast while in the South Coast, Midlands and Zululand and Irrigated regions it varies between 0.00% and 0.42%, 0.05% and 1.91% and 0.28% and 5.36% respectively. SFR is greater in clayey soils than sandier soils because clayey soils have higher water holding capacities than sandier soils.

Furthermore, the greatest SFR occurs in the Zululand and Irrigated region followed by the Midlands, North Coast and South Coast regions. Regional differences in SFR are attributed to variations in evapotranspiration rates and climate in the homogenous regions.

In conclusion, soil and water conservation structures cause decreases in stream flow across all regions, soil types and practices. This is because soil and water conservation structures intercept runoff and increase the amount of water infiltration into the soil thereby slowing down and reducing the amount of water running off. According to Jewitt *et al.* (2009), activities whose impacts on SFR are greater than 10% of the MAR should be considered to be declared as a SFRAs. Therefore, the SFR caused by soil and water conservation structures is insignificant (*i.e.* < 5.5%) and does not necessitate their declaration as SFRAs as contained in the National Water Act of South Africa. However, if soil and water conservation structures were to be eliminated, SFR would decrease although soil erosion would increase which is undesirable and will contribute to unsustainable long term production.

7.5 References

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7.6 Appendix 7.1: Total Stream Flows and Stream Flow Reductions

The total stream flows and SFRs due to soil and water conservation structures in sugarcane fields are shown in Table 7.2.

Table 7.2 Total stream flows and SFRs due to soil and water conservation structures in sugarcane fields

Simulated Mean Annual Stream Flow																							
Clay				Loamy sand				Sand				Sandy clay				Sandy clay loam				Sandy loam			
No structure (mm)	Soil and water conservation structure (mm)	SFR (mm)	SFR (%)	No structure (mm)	Soil and water conservation structure (mm)	SFR (mm)	SFR (%)	No structure (mm)	Soil and water conservation structure (mm)	SFR (mm)	SFR (%)	No structure (mm)	Soil and water conservation structure (mm)	SFR (mm)	SFR (%)	No structure (mm)	Soil and water conservation structure (mm)	SFR (mm)	SFR (%)	No structure (mm)	Soil and water conservation structure (mm)	SFR (mm)	SFR (%)
337	337	0.00	0.00	334	334	-0.07	-0.02	351	351	-0.07	-0.02	338	337	-0.51	-0.15	318	318	-0.44	-0.14	327	327	-0.07	-0.02
337	337	0.00	0.00	334	334	-0.07	-0.02	351	351	-0.07	-0.02	338	337	-0.51	-0.15	318	318	-0.44	-0.14	327	327	-0.07	-0.02
337	337	0.00	0.00	334	334	-0.07	-0.02	351	351	-0.07	-0.02	338	337	-0.51	-0.15	318	318	-0.44	-0.14	327	327	-0.07	-0.02
313	312	-0.18	-0.06	319	318	-0.12	-0.04	329	329	-0.12	-0.04	314	313	-0.71	-0.22	308	307	-0.50	-0.16	315	315	-0.13	-0.04
345	345	-0.04	-0.01	342	342	-0.09	-0.03	360	360	-0.09	-0.02	345	345	-0.53	-0.15	325	325	-0.46	-0.14	335	335	-0.09	-0.03
345	345	-0.04	-0.01	342	342	-0.09	-0.03	360	360	-0.09	-0.02	345	345	-0.53	-0.15	325	325	-0.46	-0.14	335	335	-0.09	-0.03
345	345	-0.04	-0.01	342	342	-0.09	-0.03	360	360	-0.09	-0.02	345	345	-0.53	-0.15	325	325	-0.46	-0.14	335	335	-0.09	-0.03
317	317	-0.12	-0.04	323	323	-0.12	-0.04	335	334	-0.12	-0.04	318	318	-0.68	-0.21	312	311	-0.51	-0.17	320	319	-0.13	-0.04
337	337	-0.37	-0.11	335	335	-0.25	-0.07	352	351	-0.21	-0.06	339	338	-0.88	-0.26	320	319	-0.99	-0.31	328	327	-0.26	-0.08
337	337	-0.37	-0.11	335	335	-0.25	-0.07	352	351	-0.21	-0.06	339	338	-0.88	-0.26	320	319	-0.99	-0.31	328	327	-0.26	-0.08
337	337	-0.37	-0.11	335	335	-0.25	-0.07	352	351	-0.21	-0.06	339	338	-0.88	-0.26	320	319	-0.99	-0.31	328	327	-0.26	-0.08
314	313	-0.68	-0.22	319	319	-0.46	-0.14	330	329	-0.35	-0.11	316	315	-1.32	-0.42	310	309	-1.18	-0.38	316	316	-0.43	-0.13
345	345	-0.35	-0.10	342	342	-0.28	-0.08	361	361	-0.21	-0.06	347	346	-0.88	-0.25	327	326	-0.96	-0.29	335	335	-0.28	-0.08
345	345	-0.35	-0.10	342	342	-0.28	-0.08	361	361	-0.21	-0.06	347	346	-0.88	-0.25	327	326	-0.96	-0.29	335	335	-0.28	-0.08
345	345	-0.35	-0.10	342	342	-0.28	-0.08	361	361	-0.21	-0.06	347	346	-0.88	-0.25	327	326	-0.96	-0.29	335	335	-0.28	-0.08
319	318	-0.66	-0.21	324	323	-0.44	-0.14	335	335	-0.35	-0.11	321	319	-1.32	-0.41	314	312	-1.15	-0.37	320	320	-0.41	-0.13
363	363	-0.09	-0.02	354	354	-0.09	-0.02	379	379	-0.04	-0.01	364	363	-0.81	-0.22	333	333	-0.56	-0.17	344	344	-0.06	-0.02
363	363	-0.09	-0.02	354	354	-0.09	-0.02	379	379	-0.04	-0.01	364	363	-0.81	-0.22	333	333	-0.56	-0.17	344	344	-0.06	-0.02
363	363	-0.09	-0.02	354	354	-0.09	-0.02	379	379	-0.04	-0.01	364	363	-0.81	-0.22	333	333	-0.56	-0.17	344	344	-0.06	-0.02
316	315	-0.60	-0.19	320	320	-0.12	-0.04	333	333	-0.09	-0.03	315	314	-1.46	-0.46	308	307	-0.97	-0.31	316	316	-0.10	-0.03
377	377	-0.12	-0.03	367	367	-0.10	-0.03	392	392	-0.03	-0.01	375	375	-0.81	-0.22	345	345	-0.54	-0.16	356	356	-0.04	-0.01
377	377	-0.12	-0.03	367	367	-0.10	-0.03	392	392	-0.03	-0.01	375	375	-0.81	-0.22	345	345	-0.54	-0.16	356	356	-0.04	-0.01
377	377	-0.12	-0.03	367	367	-0.10	-0.03	392	392	-0.03	-0.01	375	375	-0.81	-0.22	345	345	-0.54	-0.16	356	356	-0.04	-0.01
322	321	-0.60	-0.19	326	325	-0.13	-0.04	339	339	-0.07	-0.02	321	319	-1.40	-0.44	313	312	-0.90	-0.29	322	321	-0.10	-0.03
364	364	-0.71	-0.19	355	355	-0.47	-0.13	380	379	-0.35	-0.09	366	365	-1.47	-0.40	336	334	-1.54	-0.46	345	344	-0.46	-0.13

Simulated Mean Annual Stream Flow																							
Clay				Loamy sand				Sand				Sandy clay				Sandy clay loam				Sandy loam			
No structure (mm)	Soil and water conservation structure (mm)	SFR (mm)	SFR (%)	No structure (mm)	Soil and water conservation structure (mm)	SFR (mm)	SFR (%)	No structure (mm)	Soil and water conservation structure (mm)	SFR (mm)	SFR (%)	No structure (mm)	Soil and water conservation structure (mm)	SFR (mm)	SFR (%)	No structure (mm)	Soil and water conservation structure (mm)	SFR (mm)	SFR (%)	No structure (mm)	Soil and water conservation structure (mm)	SFR (mm)	SFR (%)
364	364	-0.71	-0.19	355	355	-0.47	-0.13	380	379	-0.35	-0.09	366	365	-1.47	-0.40	336	334	-1.54	-0.46	345	344	-0.46	-0.13
364	364	-0.71	-0.19	355	355	-0.47	-0.13	380	379	-0.35	-0.09	366	365	-1.47	-0.40	336	334	-1.54	-0.46	345	344	-0.46	-0.13
319	317	-1.82	-0.57	321	321	-0.71	-0.22	334	333	-0.51	-0.15	320	317	-2.57	-0.80	312	310	-2.06	-0.66	317	317	-0.65	-0.20
378	377	-0.72	-0.19	367	367	-0.43	-0.12	393	392	-0.35	-0.09	378	377	-1.46	-0.38	348	346	-1.46	-0.42	357	357	-0.40	-0.11
378	377	-0.72	-0.19	367	367	-0.43	-0.12	393	392	-0.35	-0.09	378	377	-1.46	-0.38	348	346	-1.46	-0.42	357	357	-0.40	-0.11
378	377	-0.72	-0.19	367	367	-0.43	-0.12	393	392	-0.35	-0.09	378	377	-1.46	-0.38	348	346	-1.46	-0.42	357	357	-0.40	-0.11
325	323	-1.76	-0.54	327	326	-0.74	-0.23	340	339	-0.51	-0.15	326	323	-2.59	-0.80	317	315	-2.01	-0.64	323	322	-0.65	-0.20
118	115	-3.25	-2.76	125	124	-0.56	-0.45	136	135	-0.38	-0.28	125	121	-3.19	-2.55	115	113	-2.28	-1.98	120	120	-0.55	-0.46
118	115	-3.25	-2.76	125	124	-0.56	-0.45	136	135	-0.38	-0.28	125	121	-3.19	-2.55	115	113	-2.28	-1.98	120	120	-0.55	-0.46
118	115	-3.25	-2.76	125	124	-0.56	-0.45	136	135	-0.38	-0.28	125	121	-3.19	-2.55	115	113	-2.28	-1.98	120	120	-0.55	-0.46
101	97	-4.21	-4.16	110	109	-0.72	-0.66	116	116	-0.48	-0.42	107	103	-4.19	-3.91	105	102	-2.60	-2.48	108	108	-0.65	-0.60
125	122	-3.17	-2.53	133	132	-0.50	-0.37	145	145	-0.33	-0.23	132	129	-3.12	-2.36	122	120	-2.23	-1.83	127	127	-0.50	-0.39
125	122	-3.17	-2.53	133	132	-0.50	-0.37	145	145	-0.33	-0.23	132	129	-3.12	-2.36	122	120	-2.23	-1.83	127	127	-0.50	-0.39
125	122	-3.17	-2.53	133	132	-0.50	-0.37	145	145	-0.33	-0.23	132	129	-3.12	-2.36	122	120	-2.23	-1.83	127	127	-0.50	-0.39
104	100	-4.14	-3.99	112	112	-0.69	-0.61	119	118	-0.48	-0.41	109	105	-4.17	-3.82	107	104	-2.52	-2.35	110	110	-0.65	-0.59
128	123	-4.89	-3.83	128	126	-1.84	-1.45	138	137	-1.36	-0.99	134	129	-5.01	-3.73	123	119	-4.08	-3.32	123	122	-1.90	-1.54
128	123	-4.89	-3.83	128	126	-1.84	-1.45	138	137	-1.36	-0.99	134	129	-5.01	-3.73	123	119	-4.08	-3.32	123	122	-1.90	-1.54
128	123	-4.89	-3.83	128	126	-1.84	-1.45	138	137	-1.36	-0.99	134	129	-5.01	-3.73	123	119	-4.08	-3.32	123	122	-1.90	-1.54
113	107	-6.08	-5.36	114	112	-2.22	-1.95	119	118	-1.78	-1.49	119	113	-6.13	-5.15	114	109	-4.74	-4.16	112	110	-2.18	-1.95
134	130	-4.63	-3.44	135	134	-1.62	-1.20	147	146	-1.21	-0.82	142	137	-4.86	-3.43	130	126	-4.03	-3.11	130	129	-1.69	-1.30
134	130	-4.63	-3.44	135	134	-1.62	-1.20	147	146	-1.21	-0.82	142	137	-4.86	-3.43	130	126	-4.03	-3.11	130	129	-1.69	-1.30
134	130	-4.63	-3.44	135	134	-1.62	-1.20	147	146	-1.21	-0.82	142	137	-4.86	-3.43	130	126	-4.03	-3.11	130	129	-1.69	-1.30
115	109	-5.99	-5.19	116	114	-2.25	-1.93	122	120	-1.82	-1.49	121	115	-6.05	-5.00	116	111	-4.71	-4.06	114	112	-2.17	-1.90
164	164	-0.12	-0.07	161	161	-0.07	-0.05	177	177	-0.03	-0.02	165	164	-0.60	-0.37	147	147	-0.45	-0.30	155	155	-0.07	-0.05
164	164	-0.12	-0.07	161	161	-0.07	-0.05	177	177	-0.03	-0.02	165	164	-0.60	-0.37	147	147	-0.45	-0.30	155	155	-0.07	-0.05
164	164	-0.12	-0.07	161	161	-0.07	-0.05	177	177	-0.03	-0.02	165	164	-0.60	-0.37	147	147	-0.45	-0.30	155	155	-0.07	-0.05
130	129	-0.74	-0.57	136	136	-0.18	-0.13	142	141	-0.15	-0.11	129	128	-1.38	-1.07	130	129	-0.83	-0.64	135	135	-0.18	-0.13
173	173	-0.06	-0.03	170	170	-0.06	-0.03	187	187	-0.04	-0.02	174	173	-0.54	-0.31	155	155	-0.43	-0.27	163	163	-0.06	-0.04
173	173	-0.06	-0.03	170	170	-0.06	-0.03	187	187	-0.04	-0.02	174	173	-0.54	-0.31	155	155	-0.43	-0.27	163	163	-0.06	-0.04
173	173	-0.06	-0.03	170	170	-0.06	-0.03	187	187	-0.04	-0.02	174	173	-0.54	-0.31	155	155	-0.43	-0.27	163	163	-0.06	-0.04
131	130	-0.68	-0.52	137	137	-0.19	-0.14	143	143	-0.15	-0.10	130	129	-1.38	-1.06	131	130	-0.81	-0.62	136	136	-0.17	-0.13
165	165	-0.69	-0.42	162	161	-0.49	-0.30	178	178	-0.28	-0.16	167	166	-1.22	-0.73	150	148	-1.31	-0.88	155	155	-0.50	-0.32

Simulated Mean Annual Stream Flow																							
Clay				Loamy sand				Sand				Sandy clay				Sandy clay loam				Sandy loam			
No structure (mm)	Soil and water conservation structure (mm)	SFR (mm)	SFR (%)	No structure (mm)	Soil and water conservation structure (mm)	SFR (mm)	SFR (%)	No structure (mm)	Soil and water conservation structure (mm)	SFR (mm)	SFR (%)	No structure (mm)	Soil and water conservation structure (mm)	SFR (mm)	SFR (%)	No structure (mm)	Soil and water conservation structure (mm)	SFR (mm)	SFR (%)	No structure (mm)	Soil and water conservation structure (mm)	SFR (mm)	SFR (%)
165	165	-0.69	-0.42	162	161	-0.49	-0.30	178	178	-0.28	-0.16	167	166	-1.22	-0.73	150	148	-1.31	-0.88	155	155	-0.50	-0.32
165	165	-0.69	-0.42	162	161	-0.49	-0.30	178	178	-0.28	-0.16	167	166	-1.22	-0.73	150	148	-1.31	-0.88	155	155	-0.50	-0.32
133	131	-1.89	-1.42	137	136	-0.71	-0.52	142	142	-0.58	-0.41	134	131	-2.55	-1.91	133	131	-1.96	-1.47	136	135	-0.73	-0.53
174	174	-0.74	-0.42	170	170	-0.41	-0.24	187	187	-0.26	-0.14	176	175	-1.19	-0.68	157	156	-1.15	-0.73	164	163	-0.46	-0.28
174	174	-0.74	-0.42	170	170	-0.41	-0.24	187	187	-0.26	-0.14	176	175	-1.19	-0.68	157	156	-1.15	-0.73	164	163	-0.46	-0.28
174	174	-0.74	-0.42	170	170	-0.41	-0.24	187	187	-0.26	-0.14	176	175	-1.19	-0.68	157	156	-1.15	-0.73	164	163	-0.46	-0.28
134	132	-1.84	-1.37	138	137	-0.69	-0.50	144	143	-0.58	-0.40	135	132	-2.54	-1.88	134	132	-1.95	-1.46	137	136	-0.67	-0.49

8 DISCUSSION, CONCLUSIONS AND RECOMMENDATIONS FOR FURTHER RESEARCH

A discussion of the six chapters presented above together with the conclusions and recommendations for future research are contained in this chapter.

8.1 Study Objectives

The aim of this research was to develop updated design norms for soil and water conservation structures in the sugar industry of South Africa. The specific objectives presented in each chapter to achieve the major objective of this study are discussed in the following sections.

8.2 Review of Design Norms for Soil and Water Conservation Structures in the Sugar Industry

Soil erosion is a serious problem emanating from a combination of agricultural intensification, soil degradation and intense rainstorms. Estimates show that South Africa has an average soil erosion rate of 12.3 $t.ha^{-1}.year^{-1}$ (Le Roux *et al.*, 2008) while the estimated rate of soil formation ranges between 0.25 and 0.38 $t.ha^{-1}.year^{-1}$. In addition, unsustainable soil losses result in crop yield reductions, hence the need to limit soil losses to sustainable levels. Traditionally, contour banks or terrace roads and waterways are the mechanical means of soil conservation used in the South African sugar industry, and the standards and guidelines for the design of soil conservation structures were published by SASA (2002). Platford (1987) developed a nomograph for determining the spacing of soil and water conservation structures in the sugar industry of South Africa by employing observations from runoff plots and the long term average annual soil loss simulated using the Universal Soil Loss Equation (USLE). However, the USLE estimates annual soil loss and yet erosion occurs on an event basis. Similarly, the Revised Universal Soil Loss Equation (RUSLE) and Soil Loss Estimator for Southern Africa (SLEMSA) predict annual soil loss while the Revised Universal Soil Loss Equation - Version

2 (RUSLE2) predicts the long-term average soil loss on a given day. On the other hand, the Modified Universal Soil Loss Equation (MUSLE) is an event based model capable of predicting sediment yield on an event basis. Therefore, the updated design norms should be developed using an event based erosion prediction model since erosion occurs on an event basis, and it is expected that most of the soil erosion occurs from only a few extreme events per year (Schulze *et al.*, 2011).

Hydrologic design is vital and it is a precursor to the hydraulic design of soil and water conservation structures. Currently, the design norms employed in the sugar industry of South Africa specify a 10 year return period for the design of soil and water conservation structures but are not clear on the duration of the rainfall events that are used in their designs, yet a 10 year return period, 24 hour storm is the minimum recommended. However, increases in both design rainfall and design floods are anticipated in South Africa as a result of climate change. Hence, the 10 year return period currently recommended may not be adequate due to the projected levels of risk and the fact that a few large events are likely to be responsible for the majority of the erosion.

Climate greatly influences erosion controlling factors followed by the soil parent material, while the influence of slope factors are masked by climatic and parent material effects. However, the nomograph for the design of soil and water conservation structures in the sugar industry does not include any regional variations of climate and the impact on soil erosion and runoff. Therefore, it is important to incorporate regional variations in climate in the updated design norms for the design of soil and water conservation structures.

From the literature review, it was evident that differences exist between design norms in the National Soil Conservation Manual and norms used in the sugar industry (*e.g*. maximum slope, cover factors for sugarcane and maximum contour spacing). In addition, the current sugar industry design norms advocate for specific designs whenever slopes are less than 3% or greater than 30% although the design nomograph used in the sugar industry caters for slopes up to 40%. Some slopes in the sugar industry exceed 40% and yet the nomograph has a maximum slope of 40% and cannot be used to design structures on land were slopes are greater than 40% or less than 3%. Hence, these anomalies need to be revised and harmonised in the updated design norms for the design of soil and water conservation structures.

Crop rotation is recommended in sugar production, ensuring soil fertility and reduction of pests and diseases, yet this important practice is not included in the design norms for soil and water conservation structures in the sugar industry. The design nomograph used in the sugar industry does not include vulnerability during break cropping where the cover may be reduced as a result of field rejuvenation and replanting of sugarcane.

In conclusion, there is a need to accommodate climate change variations, significant events of soil erosion, production and management practices, unforeseen events which may occur, and regional differences in climate, soils and slopes in future design norms for soil and water conservation structures in the sugar industry of South Africa.

8.3 Verification of Runoff Volume, Peak Discharge and Sediment Yield

Verification of runoff, peak discharge and sediment yield were based on the La Mercy catchments and clean data set established in Chapter 3, and simulations were conducted by the Agricultural Catchments Research Unit (*ACRU*) model. In general, the relative sequences and orders of magnitude of runoff from the La Mercy catchments were reasonably simulated under both bare fallow and sugarcane land cover conditions. Furthermore, the association between observed and simulated runoff volumes were reasonably good as depicted by the regression statistics (*i.e.* slopes of regression lines close to unity and $R^2 \geq 0.6$). Nonetheless, over and under simulations were evident and these could be attributed to random errors in the measurement of daily runoff volumes and the fact that the *ACRU* model is not an optimising model except for Catchment 104 under bare fallow conditions where systematic errors could have occurred in the measurement of daily runoff volumes.

Peak discharge simulations and verifications followed similar trends exhibited by simulated and verified daily runoff volumes under each catchment thereby confirming that peak discharge is driven by runoff volume. The correlations between observed and simulated peak discharge across all four catchments was acceptable (*i.e.* slopes of regression lines close to unity and $R^2 \geq 0.6$), although incidences of both over and under simulations were still evident and these could be attributed to the same reasons cited under verification of runoff volumes. Verification of sediment yield also yielded acceptable results, with the association between simulated and observed sediment yield events reasonably good.

In conclusion, the *ACRU* model was found to be suitable in the simulation of runoff volume, peak discharge and sediment yield from catchments under both bare fallow and sugarcane land cover and with various management practices in South Africa. Consequently, the *ACRU* model was applied with confidence in the development of updated design norms for soil and water conservation structures in the sugar industry in South Africa as presented in Chapter 5.

8.4 Development and Assessment of an Updated Tool for the Design of Soil and Water Conservation Structures in the Sugar Industry of South Africa

The study area consisted of sugarcane growing areas in South Africa, categorised into homogenous zones on the basis of growth cycle lengths as South Coast, North Coast, Zululand and Irrigated, and Midlands. The respective ratoon lengths for the regions were 16, 13, 12 and 21 months while the areas comprised six soil textural classes namely clay, loamy sand, sand, sandy clay, sandy clay loam and sandy loam. The observed data consisted of daily rainfall for the period 1950 – 2017, maximum and minimum temperature and A-pan data for the period 1950 – 1999. Prior to the development and assessment of the updated tool hereby named Contour Spacing Design Tool (CoSDT), various *ACRU* parameters were estimated based on the verifications presented in Chapter 4 and expert opinion. Consequently, simulations of runoff, peak discharge and sediment yield were conducted with the *ACRU* model and the exhibited trends analysed. From the simulated results, the CoSDT was developed and emphasis was placed on developing a tool that was robust but simple to apply, based on sustainable soil loss limits, includes regional variations of climate and their impacts on soil erosion and runoff and also include vulnerability during break cropping. Finally, designs from the CoSDT were compared against designs from the current sugar industry design nomograph and designs conducted by specialists in the sugar industry which were based on the SASRI nomograph.

Generally, the most amount of simulated runoff was in the North Coast followed by the South Coast, Midlands, and Zululand and Irrigated regions which was logical considering that rainfall was highest in the North Coast followed by the South Coast, Midlands, and Zululand and Irrigated regions. However, the largest amount of sediment yield was simulated for the South Coast followed by North Coast, Zululand and Irrigated and the Midlands regions and this was attributed to the differences in rainfall intensity and ratoon lengths in the homogenous climatic zones. The respective 30 minute, 2 year rainfall intensity and ratoon lengths for the regions were 60, 53, 50 and 68 $mm.h^{-1}$ and 16, 13, 12 and 21 months.

With regards to variation of sediment yield across the different soil textural classes, sandier soils were the more susceptible to erosion than clayey soils in the North Coast, South Coast and Zululand and Irrigated regions. This trend was expected because sandier soils are less cohesive than clayey soils and hence more unstable and at greater risk of erosion. However, clayey soils were more susceptible to erosion than the sandier soils in the Midlands regions. Initially, it was suspected that the rainfall of higher intensity received in the Midlands region compared to the North Coast, South Coast and Zululand and Irrigated regions was responsible for the difference in trends. However, further investigations on the effects of varying rainfall intensity to lower values showed that clayey soils were still more susceptible to erosion than sandier soils. Therefore, it was postulated that trend exhibited in the Midlands was attributed to the relatively low daily rainfall occurring more frequently compared to the North Coast, South Coast and Zululand and Irrigated regions. This is because, the frequently occurring low rainfall makes the soils wet and with clayey soils having poorer drainage than sandier soils, more runoff is generated from the clayey soils thus increasing the risk of sediment yield.

Comparisons of contour bank spacing designs from the CoSDT and the current sugar industry design nomograph showed differences resulting in both over and under designs depending on the scenario and region. The source of discrepancies was attributed to the fact that the current sugar industry design nomograph was developed using the USLE and average values representing the entire sugar industry while the CoSDT was developed using the MUSLE with the parameters representative of each region in the sugar industry. For example, the R factor which drives erosion in the USLE and used in the development of the current sugar industry design nomograph was static and constant and yet rainfall erosivity is not uniformly distributed throughout the year. On the other hand, the storm flow factor which drives sediment yield in the MUSLE varies regionally and across regions. Similarly, static C factors are used in the USLE whereas C factors used in the MUSLE vary depending on stage of sugarcane growth (*i.e.* 0.60 at planting of sugarcane and 0.01 at full canopy establishment).

Furthermore, development of the current sugar industry design nomograph was based on subjective judgement by Platford (1987) which could have been another source of discrepancies. Equally, discrepancies in designs prepared by specialists in the sugar industry and designs from the CoSDT were evident and the reasons for the differences are similar to those presented under comparisons of designs of contour bank spacings from the CoSDT and the current sugar industry design nomograph.

In conclusion, the CoSDT is more representative of conditions in the sugar industry of South Africa, and it should be employed in place of the current sugar industry design nomograph developed by Platford (1987). The CoSDT is robust but simple to use, it accounts for vulnerability during break cropping and it accounts for variations of climate and their impacts on soil erosion and runoff. Furthermore, it is based on sustainable soil loss limits of 5 $t.ha^{-1}.year^{-1}$.

8.5 System Design Criteria and the Economic Impact of Varying Design Return Periods

This study was based on data and results of simulations of runoff, peak discharge and sediment yield using the *ACRU* model for the four homogenous climatic zones presented in Chapter 5.

The total number and magnitudes of sediment yield events contributing to annual sediment yield varied annually and across regions. The variations within a given region were attributed to differences in temporal distribution of rainfall and harvesting periods whereas variations across regions were attributed to differences in spatial distribution of rainfall, differences in ratoon lengths and differences in harvesting periods. Furthermore, very few events constituted significant percentages (*i.e.* 21 – 95%) towards the annual sediment yield, and 0.2% of the sediment yield events in each region constituted 35%, 43%, 38% and 19% of the total simulated sediment yield in the North Coast, South Coast, Zululand and Irrigated and Midlands regions respectively. Hence, averaging of annual sediment yield and design of soil and water conservation structures should be based on the few sediment yield events which contribute to annual erosion.

Generally, extreme events of sediment yield were not necessarily caused by the most extreme rainfall, runoff and peak discharge events. This was attributed to the variations in crop cover at different stages of sugarcane growth which impact on the sediment yield generated. However, when simulations were conducted for the same scenarios but with green manuring practices after the last ratoon crop and before replant as opposed to bare fallow conditions, the sediment yield drastically reduced and rainfall events of higher return periods generated runoff of lower return periods. In addition, rainfall events generated runoff and peak discharge events of lower return periods and sediment yield events of higher return periods. This was attributed to variations in antecedent soil moisture conditions which impact on the runoff and peak discharge generated.

In order to maintain sediment yield within sustainable limits of 5 $t.ha^{-1}$, return periods of rainfall events generating the 5 $t.ha^{-1}$, were used as the control point and rounded to the nearest multiple of 10 to obtain the recommended design return period. Hence, the 20 year return period was recommended for the design of soil and water conservation structures. The cost implication of varying design return periods from the minimum 10 year return period to the 20 year return period was 16%, 33%, 28% and 35% South African rand for the North Coast, South Coast, Midlands and Zululand and Irrigated regions respectively. Due to the fact that soil erosion is associated with adverse effects on sustainable crop production and also increases in costs of replanting washed away crops, the 20 year return period was recommended for the design of soil and water conservation structures. Additionally, designs for soil and water conservation structures should be conducted for bare fallow conditions which represent conditions when soils are most susceptible to erosion. Finally, considering that the simulations used in this study are for one historical rainfall sequence and fixed planting dates, there is need to conduct iterative runs for different planting dates and perhaps using stochastic climates as input.

8.6 Impacts of Soil and Water Conservation Structures on Stream Flow Reduction Activities in the Sugar Industry of South Africa

Similar to Section 8.5, this study was based on the study area, data and simulations of runoff with the *ACRU* model shown in Chapter 5.

Stream Flow Reduction (SFR) as a result of soil and water conservation structures varied between 0.02% and 0.80% in the North Coast while in the South Coast, Midlands and Zululand and Irrigated regions it varied between 0.00% and 0.42%, 0.05% and 1.91% and 0.28% and 5.36% respectively. Furthermore, SFR was greater in clayey soils than sandier soils because clayey soils have higher water holding capacities than sandier soils. In terms of regions, the Zululand and Irrigated region registered the greatest amount of SFR followed by the Midlands, North Coast and South Coast regions. This was attributed to the regional differences in evapotranspiration rates and climate in the homogenous regions.

It was evident that soil and water conservation structures caused decreases in stream flows across all regions, soil types and practices. The decreases were because soil and water conservation structures intercept runoff and increase the amount of water infiltrating into the soil thereby slowing down and reducing the amount of water running off. Nonetheless, the SFR caused by soil and water conservation structures was insignificant (*i.e.* < 5.5%) and would not likely necessitate their declaration as SFR activities. This is because, for an activity to be declared a SFR activity, its impact on SFR should be greater than 10% of the Mean Annual Runoff. However, if soil and water conservation structures were to be eliminated, SFR would decrease although soil erosion would increase which is undesirable and will contribute to unsustainable long term production.

8.7 Achievement of Objectives and Novel Aspects of the Study

A new and updated tool (CoSDT) for the design of soil and water conservation structures in the sugar industry of South Africa has been generated by this research. The CoSDT is robust but simple to apply. In addition, it is based on sustainable soil loss limits of 5 $t.ha^{-1}.year^{-1}$, includes regional variations of climate and their impact on soil erosion and runoff and also includes vulnerability during break cropping. Consequently, the design of soil and water conservation structures together with soil loss estimates emanating from a given practice in a specific region (*i.e.* North Coast, South Coast, Midlands and Zululand and Irrigated) in the sugar industry of South Africa can be achieved with the CoSDT. Generally, the largest amount of sediment yield occurred in the South Coast followed by North Coast, Zululand and Irrigated and the Midlands regions. With regards to variation of sediment yield across the different soil textural classes, sandier soils were the more susceptible to erosion than clayey soils in the North Coast, South Coast and Zululand and Irrigated regions whereas clayey soils were more susceptible to erosion than sandier soils in the Midlands region. In relation to system design criteria for soil and water conservation structures, the 20 year return period has been recommended by this research and designs should be conducted for bare fallow conditions which represent conditions when soils are most susceptible to erosion. In addition, SFR caused by soil and water conservation structures has been found to be insignificant and would not likely necessitate their declaration as SFR activities.

8.8 Trends in Runoff, Peak Discharge and Sediment Yield from Catchments under Bare Fallow Conditions and Sugarcane Production

Data from four research catchments at La Mercy that used to be located on the site that now hosts the King Shaka International airport were analysed. The data comprised of daily rainfall and runoff records for the period 1978 – 1995, peak discharge and sediment yield data for the period 1984 – 1995 which were checked for errors by Smithers *et al.* (1996) and the probable inconsistencies in observed data between catchments clarified. The observed data were further quality controlled and further inconsistent records excluded before analysis of trends commenced. The inconsistent records which were excluded comprised daily runoff volumes equal to zero but with daily rainfall greater than or equal to 25 mm, daily rainfall depth equal to zero but daily runoff volume greater than zero, daily peak discharge values for which either rainfall depth or runoff volume was lacking and sediment yield records for which no runoff volume was available. Analyses of trends in runoff, peak discharge and sediment yield from catchments under bare fallow conditions and sugarcane production were then conducted using the clean data set.

Under bare fallow conditions, runoff was generally found to be inversely proportional to the length of overland flow, which observation is in agreement with Stomph *et al.* (2002) who noted that shorter overland flow paths generate more runoff than longer overland flow paths. Furthermore, the impacts of runoff potentials of soils on generation of runoff were evident although the effects of catchment steepness on runoff generation were not evident. Hence, it appears the effects of overland flow distance and soils' runoff potentials masked the effects of catchment steepness on runoff generation. Under sugarcane land cover conditions, minimum tillage practice reduced runoff to a greater extent than conventional tillage practices. This observation conforms to studies conducted by Haywood and Mitchell (1987). Unlike under bare fallow conditions, runoff was observed to increase with increases in the overland flow distance under sugarcane cover conditions which is in contradiction with observations made by Stomph *et al.* (2002). It is postulated that the effects of tillage, crop cover and other management practices supersede the effects of overland flow path on the generation of runoff. However, effects of catchment steepness, conservation structures and soils' runoff potentials on runoff generation were not evident and it could be attributed to the crop cover and other management practices masking their effects on runoff generation.

With regards to peak discharge, it was observed to increase with increases in rainfall intensity, runoff volume and catchment area which is in conformity with observations made by Schmidt and Schulze (1984) and Schulze (2011). Conversely, the influence of catchment slope on peak discharge were not evident and this could be attributed to the influence of crop cover and other management practices masking the impact of steepness on peak discharge.

Analysis of trends exhibited by sediment yield under sugarcane land cover conditions showed that only a few rainfall events were responsible for the generation of sediment yield. Therefore, these sediment yield events should be used in the calculation of average annual sediment yield. In addition, cover and management practices had a greater effect on the reduction of sediment yield than conservation structures which is in agreement with observations made by Maher (2000). However, the effects of catchment steepness and tillage practices on sediment yield were not evident and it could be attributed to the fact that soil erodibility and cover and management practices masked the effects of catchment steepness on sediment yield production.

Therefore, the factors influencing catchment responses to runoff, peak discharge and sediment yield should be taken into account when conceptualizing model parameters used in the simulation and verification of hydrological and erosion processes on an event basis.

8.9 Recommendations for Further Research

From the results presented in this study, the updated tool for the design of soil and water conservation structures in the sugar industry of South Africa should be employed in place of the current sugar industry design norms developed by Platford (1987). Nevertheless, some gaps were identified and therefore recommended for future research as follows:

(a) Much as simulations of runoff, peak discharge and sediment yield with the *ACRU* model were observed to be satisfactory, both over and under simulations were still evident. In order to improve the *ACRU* simulations further, there is a need to conduct research geared towards optimising the *ACRU* model. Optimisation should take into account the parameters associated with the factors influencing catchment responses to runoff, peak discharge and sediment yield.

(b) Temperature being a major player in the duration of ratoon lengths of sugarcane, the *ACRU* model should be modified so that ratoon lengths (*e.g.* accumulated growing degree days) can be simulated and verified as well in order to account for temperature effects on growth.

(c) Considering that the simulations used in the development of the CoSDT and subsequent analyses are for one historical rainfall sequence and fixed planting dates, there is need to conduct iterative runs for different planting dates and perhaps using stochastic climates as input.

(d) There is a need to investigate the impact of varying rainfall duration on peak discharge and its subsequent economic impact on the hydraulic design of soil and water conservation structures.

(e) Climate change impacts on hydrological processes have been projected and they vary between regions and seasons. Hence, there is need to incorporate effects of climate change in the CoSDT for the design of soil and water conservation structures in the sugar industry of South Africa.

(f) Consideration should be given to converting the CoSDT from a MS Access interface to an internet based application which would increase its accessibility by the relevant stakeholders.

(g) There is a need to investigate the climate dependent parameters (*i.e.* α and β) in the MUSLE energy driver term for the sugar industry regions in South Africa.

(h) Consideration should be given to the development of design norms for alignment, determination of hydraulic capacity, cross-section, channel slope, and outlets of soil and water conservation structures.

In conclusion, the recommendations for future research together with the methodologies presented in this study could be adopted to further improve the CoSDT for the design of soil and water conservation structures in the sugar industry of South Africa.