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

by

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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

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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.

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.

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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):