Development and assessment of an updated tool for the design of soil and water conservation structures in the sugar industry of South Africa

Daniel Otim[1,5*], Jeffrey C Smithers[1,3], Aidan Senzanje[1], Rianto van Antwerpen [2,4] and Sean L C Thornton-Dibb [6]

(1. Agricultural Engineering, School of Engineering, College of Agriculture, Engineering and Science, University of KwaZulu-Natal, Pietermaritzburg, Private Bag X01, Scottsville, 3209, South Africa;
2. South African Sugarcane Research Institute, Mount Edgecombe, 4302, South Africa;
3. National Centre for Engineering in Agriculture, University of Southern Queensland, Toowoomba, 22 Handley St, Darling Heights QLD 4350, Australia;
4. Department of Soil, Crops and Climate Sciences, University of the Free State, P O Box 339, Bloemfontein 9300, South Africa;
5. Department of Agricultural Mechanisation and Irrigation Engineering, Busitema University, P.O Box 236, Tororo, Uganda;
6. Centre for Water Resources Research, University of KwaZulu-Natal, Pietermaritzburg Campus, Private Bag X01, Scottsville, 3209, South Africa)

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. Sugarcane fields are protected against erosion through, *inter alia*, the use of engineered waterways, contour banks and spill-over roads. A comparison of design norms in the National Soil Conservation Manual and norms used in the sugar industry of South Africa clearly shows discrepancies 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 and assess updated design norms for soil and water conservation structures in the sugar industry of South Africa. The Agricultural Catchments Research Unit (*ACRU*) model estimates event-based erosion and the *ACRU* was used to conduct simulations for the different practices in the sugar industry and the outcome 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 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.

Keywords: Agricultural Catchments Research Unit, design norm, soil and water conservation, soil loss, sugarcane, South Africa

Citation: Otim, D., J. C. Smithers, A. Senzanje, R. Van Antwerpen, and S. L. C. Thornton-Dibb. 2021. 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, 23 (4):1-16.

1 Introduction

In South Africa, sugarcane is widely grown in adverse 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 the hillside at low slopes. However, sugarcane is not always grown on relatively

Received date: 2019-10-07 **Accepted date:** 2021-08-21

***Corresponding author: D. Otim**, Ph.D., Senior Lecturer in the Department of Agricultural Mechanisation and Irrigation Engineering, Busitema University, P.O Box 236, Tororo, Uganda. Email: danotim@gmail.com. Tel: +256774176824, Fax: +256454436517.

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), and 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 simulated using the Universal Soil Loss Equation (USLE) (Wischmeier and Smith, 1965; Wischmeier and Smith, 1978). However, most of the erosion occurs in relatively few events, hence the need for event modelling (Schulze, 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. Otim et al. (2019) critically reviewed various models for soil erosion estimation (e.g. USLE, Revised Universal Soil Loss Equation (RUSLE), MUSLE, RUSLE2 and Soil Loss Estimator for Southern Africa (SLEMSA)) and concluded that since erosion occurs on an event basis, the MUSLE which is an event-based model, is best suited to simulate erosion. Therefore, it is necessary to update the design norms with an event based model like the Modified Universal Soil Loss Equation (MUSLE) (Williams, 1975).

The MUSLE, developed by Williams (1975), is an empirical equation that estimates the total soil yield for a storm event (Shih 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 (Schulze, 1995a). 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 intermediate and distant 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 1 (Shih and Yang, 2009). The limits for L and S factors were determined by Wischmeier and Smith (1978) and range between 6 m and 305 m.

$$Y_{sd} = \alpha_{sy}(Q_v.q_p)^{\beta_{sy}}\ K.LS.C.P \tag{1}$$

Stormflow depth in the Agricultural Catchments Research Unit (*ACRU*) model is estimated using a modified SCS procedure shown in Equation 2 (Schmidt et al., 1987; Schulze, 1995b), while the equation for estimating peak discharge employs the SCS triangular-shaped unit hydrograph approach which is shown in Equation 3 (Schulze and Schmidt, 1995; Schulze et al., 2004).

$$Q_s = \frac{\left(P_g - I_a\right)^2}{\left(P_g - I_a + S\right)} \quad \text{for} \quad P_g > I_a \tag{2}$$

where

Q_s = stormflow depth (mm),

P_g = gross daily precipitation amount (mm),

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

S = potential maximum soil water retention (mm).

$$\Delta q_p = \frac{(0.2083A\Delta Q)}{(\frac{\Delta D}{2}+L)} \tag{3}$$

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 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 Otim (2020) 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%, 2317%, 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.

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 (DAWS, 1990; Van Staden and Smithen, 1989) 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 (Otim, 2020):

Include any regional variations of climate and the impact on soil erosion and runoff,

Account for large runoff events and how frequently these occur, and

Include vulnerability during break cropping where the cover may be reduced.

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} $year^{-1}$ (Le Roux et al., 2008; Matthee and Van Schalkwyk, 1984). 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 and 140 m (Platford, 1987; SASA, 2002). 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 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, includes regional variations of climate and their impacts on soil erosion and runoff and also include vulnerability during break cropping. Much as emphasis was placed on development of a tool or use in the sugar industry in South Africa, the methodology may be employed in the development of a similar tool for other crops and/ or areas with similar problems.

2 Materials and methods

2.1 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, 2018b), as indicated in Figure 1.

These regions receive Mean Annual Precipitation (MAP) ranging from 300 mm to more than 1100 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 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).

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). 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, 1146, 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 1143 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 (Botha et al., 1999; MacVicar et al., 1977; Smithers et al., 1995). The six textural classes are clay, loamy sand, sand, sandy clay, sandy clay loam and sandy loam.

2.2 Data

Daily observed rainfall, maximum and minimum temperature and A-pan evaporation data were obtained from the South African Sugarcane Research Institute (SASRI). The data comprises of daily observed rainfall for the period 1950 – 2017, daily maximum and minimum temperature and A-pan data for the period 1950 – 1999.

2.3 Methodology

This investigation follows an earlier study by Otim (2020), in which the runoff volume, peak discharge and sediment yield were simulated with the *ACRU* model and verified against observed data from bare fallow and sugarcane fields. Based on the results, Otim (2020) concluded that the *ACRU* model is suitable for the simulation of the runoff volume, peak discharge and sediment yield from catchments under both bare fallow and sugarcane land cover in South Africa. Subsequently, this investigation relied on results simulated with the *ACRU* model. Therefore, an overview of the steps taken to develop an updated tool for the design of soil and water conservation structures in the sugar industry of South Africa is described while the detailed methodology is presented in Otim (2020).

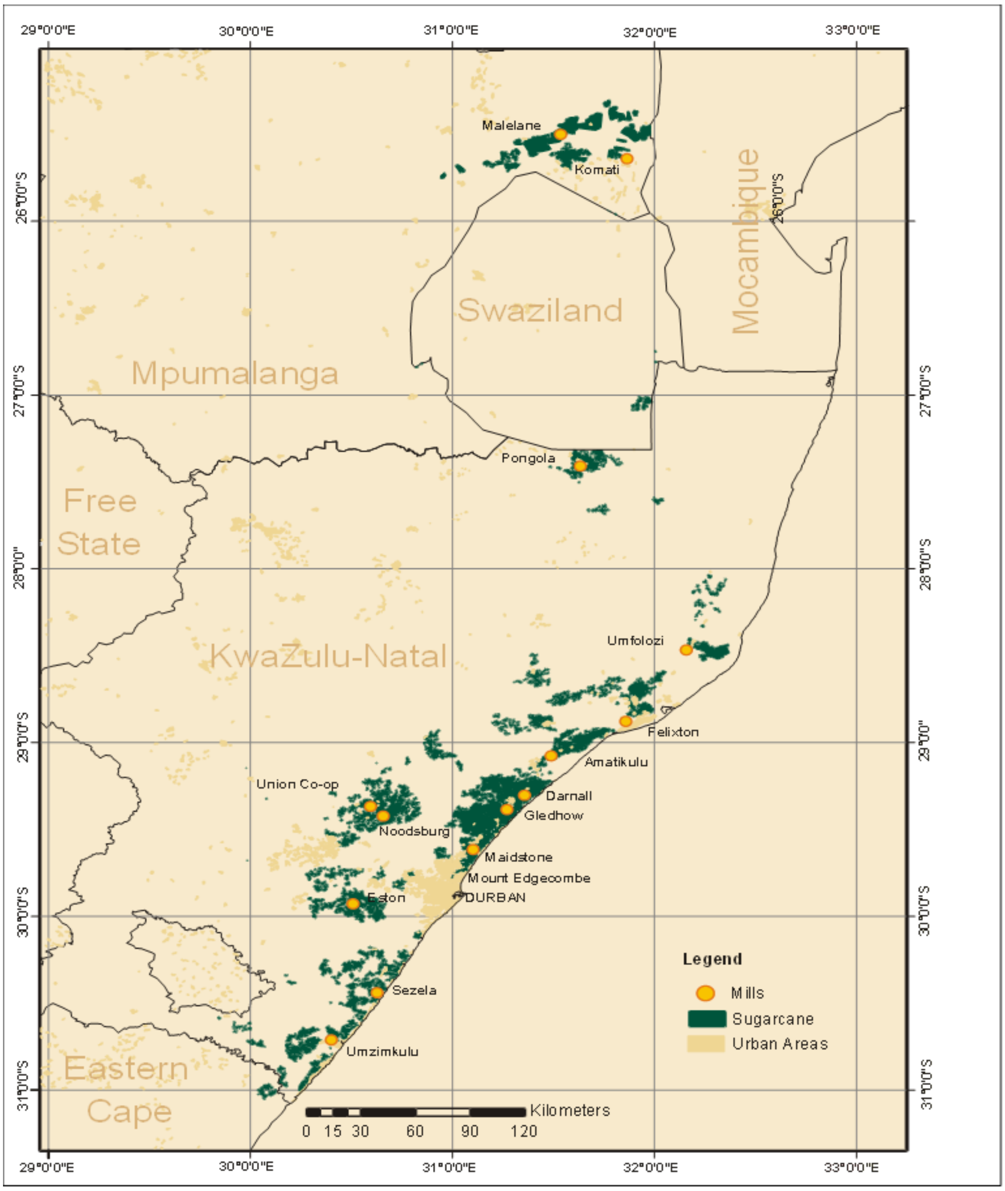

Figure 1 Location of sugarcane production areas and mills in South Africa (SASA, 2018b)

2.3.1 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.

2.3.2 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 documented by Otim (2020).

2.3.3 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. 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 presented in Otim (2020).

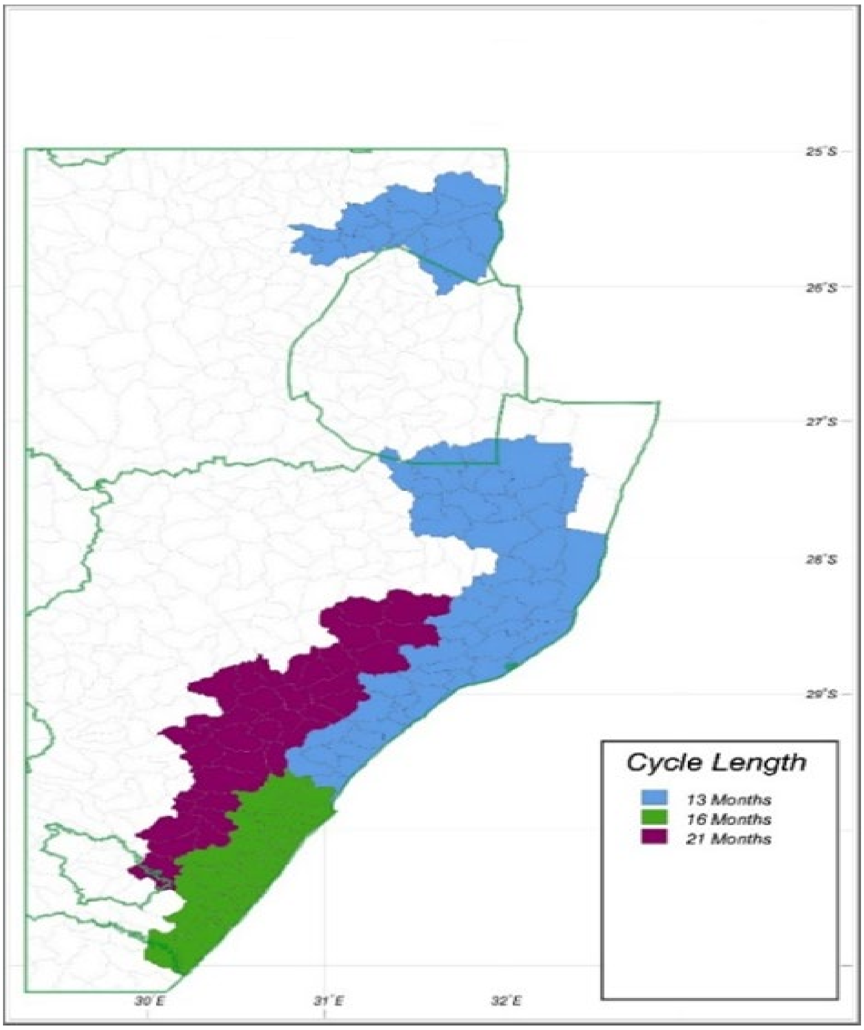

Figure 2 Regions with different sugarcane growth cycle lengths in South Africa (Schulze, 2013)

The soil *K* factors were estimated using both Level 1 and Level 3 options documented by Schulze (1995a) 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 1.

Table 1 Soil erodibility factors, *K* (Schulze, 1995a; 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

2.3.4 Simulation scenarios and parameterisation

Scenarios used in the generation of the updated design norms were conceptualised based on practices in the sugar industry of South Africa 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 2 which resulted in 46 080 scenarios simulated. *ACRU* parameters were estimated for each scenario based on verifications conducted by Otim (2020) and the parameter values are documented by Otim (2020).

Table 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

2.3.5 Development of an updated tool for the design of soil and water conservation structures in the sugar industry of South Africa

Different combinations of scenarios shown in Table 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 to 305 m) and *L* varied to limit soil losses to less than a maximum tolerable limit of 5 t ha^{-1} year^{-1} (Le Roux et al., 2008; Matthee and Van Schalkwyk, 1984). Daily maximum and minimum temperatures and average evaporation for the period 2000 – 2017 were not available from the weather stations, hence, the reason average values were used in the simulations.

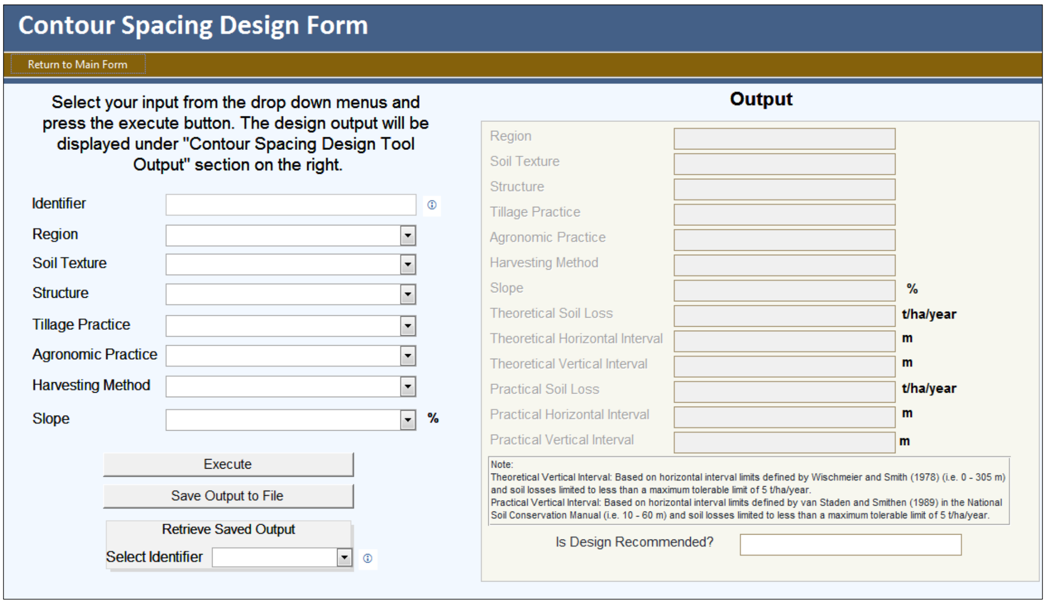

Figure 3 MS Access graphical user interface for the design of soil and water conservation structures in the sugar industry of South Africa

Furthermore, simulations with *L* factors maintained within practical limits used by Van Staden and Smithen (1989) in the National Soil Conservation Manual (*i.e.* horizontal intervals ranging from 10 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 in the sugar industry of South Africa. The CoSDT was built using MS Access as a database and a graphical user interface. The MS Access graphical user interface for the design of soil and water conservation structures is shown in Figure 3. The MS Access graphical user interface coupled with a database containing over 46 080 scenarios ensured the CoSDT was robust but simple to apply.

2.3.6 Analysis of trends in accumulated annual rainfall and runoff across different relatively homogenous climatic zones

Plots of accumulated rainfall and simulated 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.

2.3.7 Analysis of regional variations of climate on sediment yield

Plots 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.

2.3.8 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 trends 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.

2.3.9 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. For equitable comparisons, the limits of horizontal intervals range in the current sugar industry design nomograph which are from 10 to 140 m were retained in the CoSDT for the comparisons. Furthermore, soil loss estimates from the sugar industry design nomograph were calculated with the USLE and the various parameters presented by Platford (1987). Use of the CoSDT for design involves selection of typical scenarios from dropdown lists under the “Design Tool Input” section and pressing the “Execute” button as shown in Figure 3. The results for horizontal interval, vertical interval and soil loss are then returned in the “Design Tool Output” section. Steps taken to conduct designs with the sugar industry design nomograph for spacing of contour banks are presented by Platford (1987).

3 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 trends exhibited are similar irrespective of the scenario and the only differences are in the magnitudes of runoff and sediment yield. In addition, analysis of trends presented in Sections 3.1 to 3.3 was conducted using the “No Structures” scenario to eliminate effects of soil and water conservation structures on runoff and sediment yield.

3.1 Trends in accumulated annual rainfall and runoff across different homogenous climatic zones

Plots of accumulated annual rainfall for the four relatively homogenous climatic zones in the sugar industry of South Africa are shown in Figure 4 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.

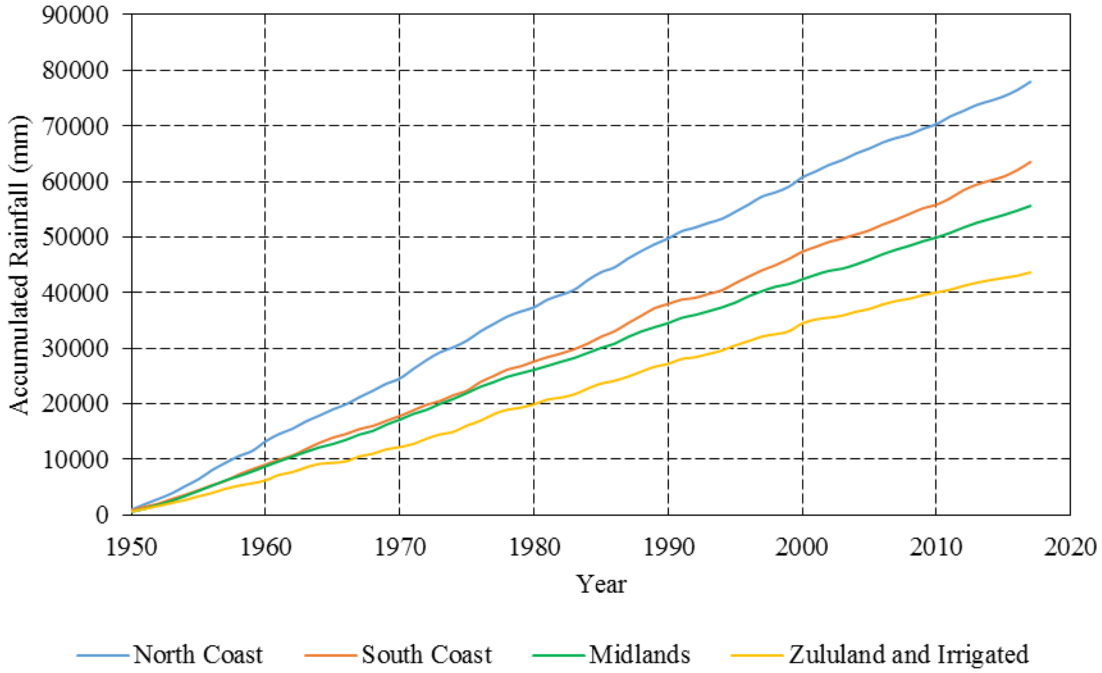

Figure 4 Trends in accumulated annual rainfall from sugarcane fields across the different relatively homogenous climatic zones

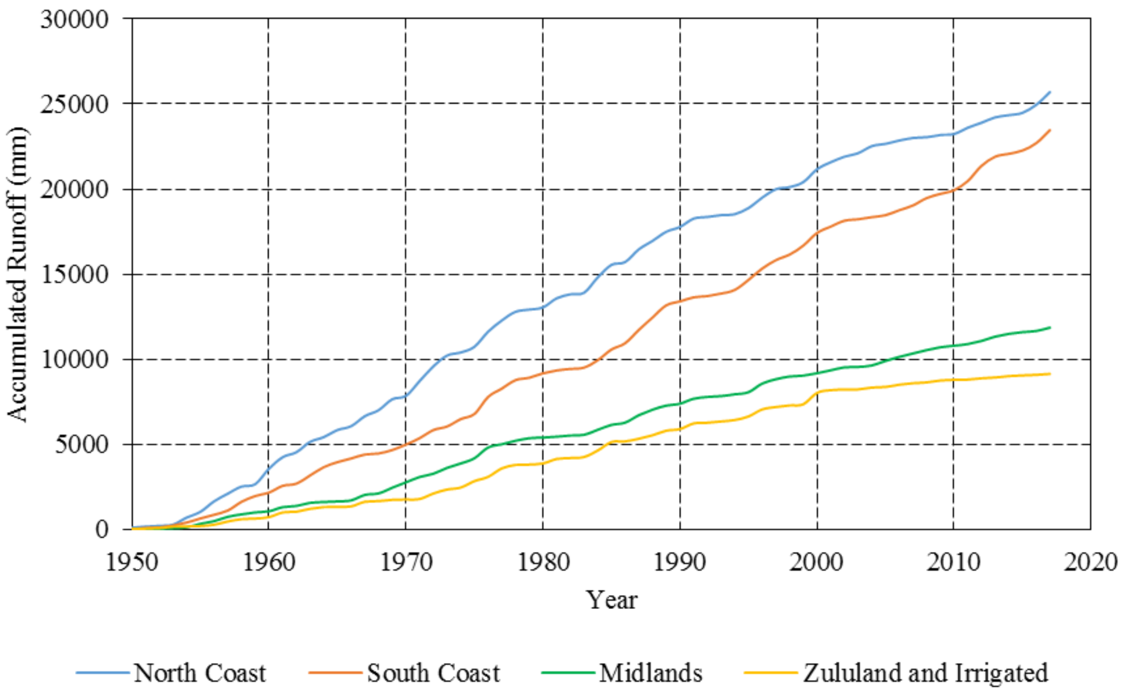

Figure 5 Trends in accumulated annual runoff from sugarcane fields across the different relatively homogenous climatic zones (Clay, No Structures, Conventional Tillage, No Green Manuring, Burnt, reburnt Harvesting and 15% slope)

From Figure 4, 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 trend exhibited is attributed to the variations in rainfall in the relatively homogenous climatic zones. Similarly in Figure 5, 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 trend exhibited is logical and attributed to the variations in rainfall in the relatively homogenous climatic zones as shown in Figure 4. 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.

3.2 Impact of regional variations of climate on sediment yield

Plots 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 6.

Generally, the largest accumulated annual sediment yield occurs in the North Coast followed by South Coast, Zululand and Irrigated and Midlands regions although the South Coast had the largest accumulated annual sediment in 2000 - 2002 and from 2010, as shown in Figure 6 for a specific scenario. The trend exhibited is reasonable and attributed to the variations in rainfall and ratoon lengths in the homogenous climatic zones. Rainfall which initiates runoff and used in the computation of peak discharge which is a driver of sediment yield, is highest in North Coast, followed by South Coast, the Midlands and Zululand and Irrigated as shown in Figure 4, while the ratoon lengths which influence sugarcane cover and hence sediment yield are 13, 16, 21 and 12 months respectively. The spike in accumulated annual sediment in 2000 - 2002 and from 2010 in the South Coast corresponds to the period when sugarcane had been harvested and the field left bare, hence being susceptible to erosion as documented by Gwapedza et al. (2018). 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.

Further comparisons of accumulated annual sediment yield shows that each region, at a given time, resulted in the largest simulated sediment yield compared to the other regions. 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.

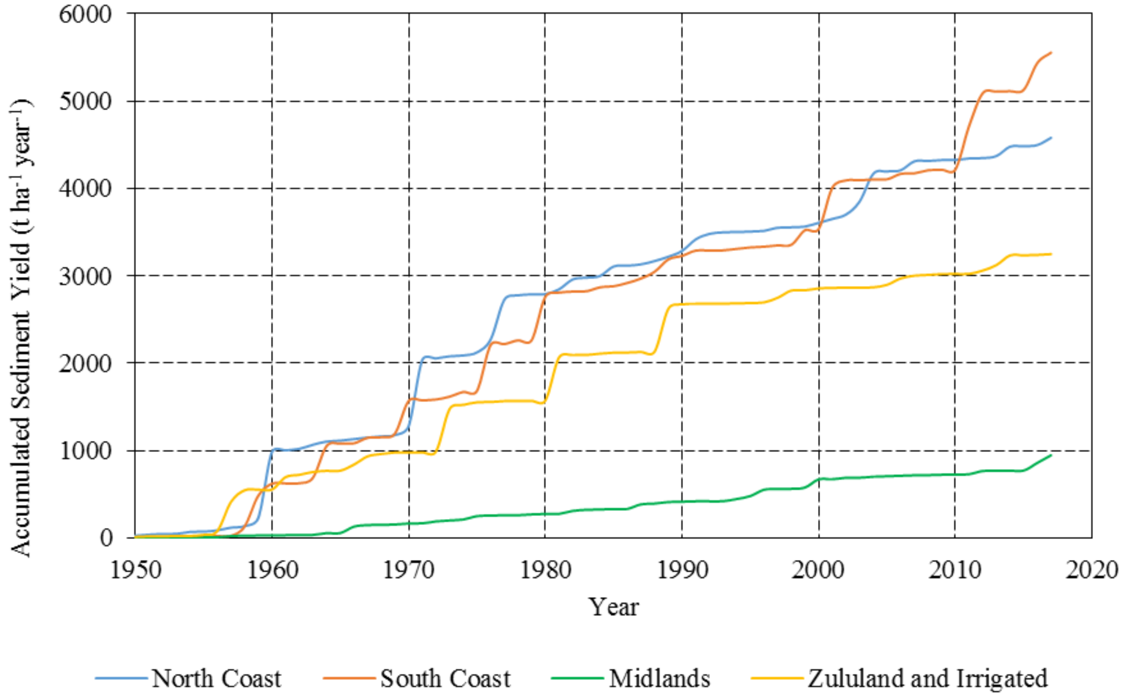

Figure 6 Trends in accumulated annual sediment yield from sugarcane fields across the different homogenous climatic zones (Clay, No Structures, Conventional Tillage, No Green Manuring, Burnt, reburnt Harvesting and 15% slope)

3.3 Impact of soil texture on sediment yield

Plots depicting trends 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 7 and Figure 8 respectively, while a discussion of the trends is presented thereafter.

From Figure 7, 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 trend is also exhibited by soils in the South Coast and Zululand and Irrigated regions. The trends 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.

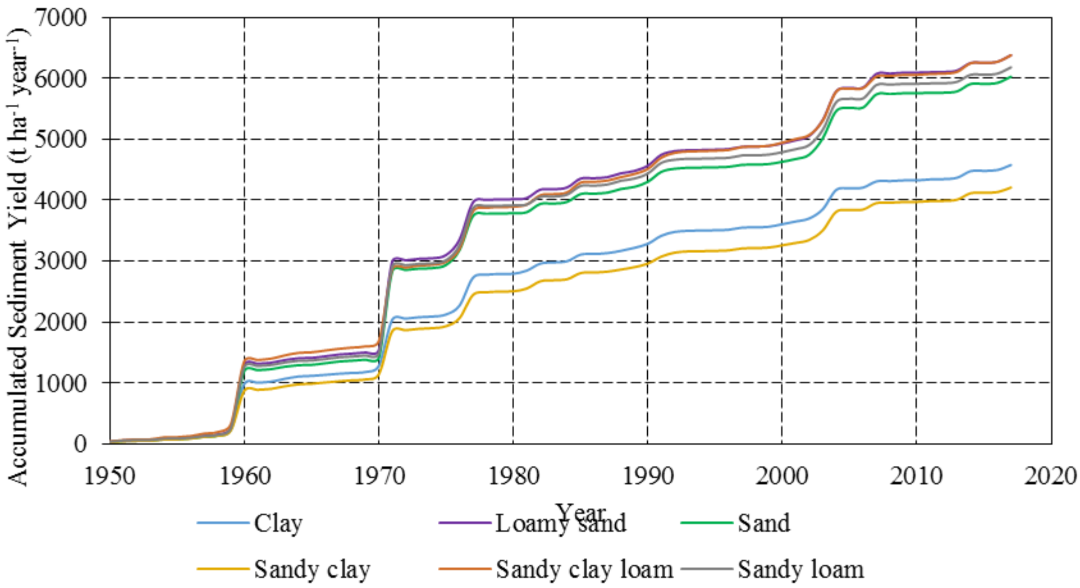

Figure 7 Trends in accumulated annual sediment yield from different soils across North Coast (All Soils, No Structures, Conventional Tillage, No Green Manuring, Burnt, reburnt Harvesting and 15% slope)

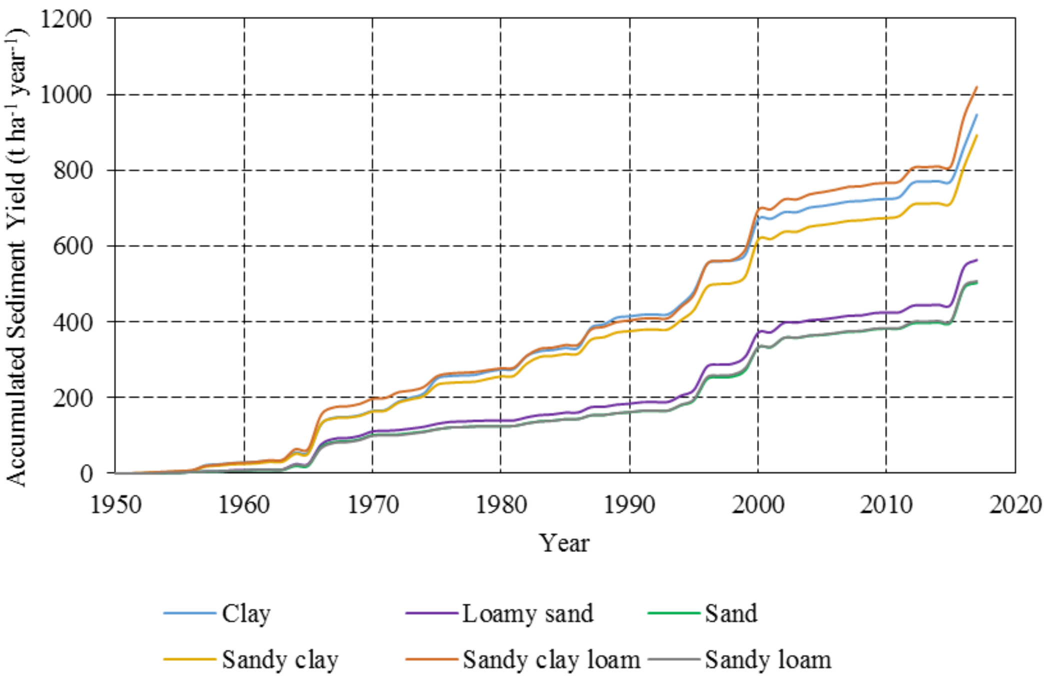

Figure 8 Trends in accumulated annual sediment yield from different soils across Midlands (All Soils, No Structures, Conventional Tillage, No Green Manuring, Burnt, reburnt Harvesting and 15% slope)

On the other hand, the erodibility trend exhibited at the Midlands is different from that at the North Coast and other regions discussed earlier, as shown in Figure 8. Four rainfall distribution zones exist in South Africa (i.e. 1, 2, 3 and 4) with zone 1 receiving the least intense rainfall and zone 4 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 trends. From Figure 8, 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 trends 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 low rainfall depths (*i.e.* ≤ 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 9. According to Manyevere et al. (2016), relationships between soil erosion and texture may vary with variations in climate. Therefore, it is postulated that the trend 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.

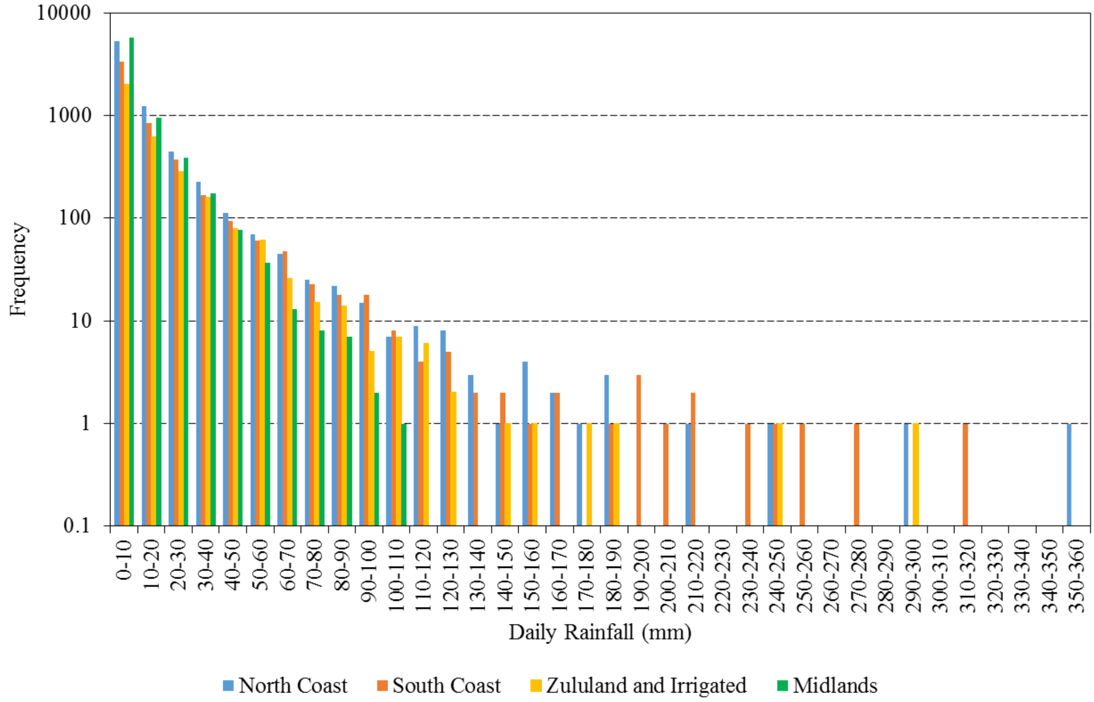

Figure 9 Frequency distribution of daily rainfall in the four regions

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

Results of select scenarios designed using the CoSDT and the current sugar industry design nomograph for spacing of contour banks are shown in Table 3 with discussions following thereafter. The soil loss estimates from the current sugar industry design nomograph were calculated using the USLE and the various parameters extracted from Platford (1987).

Differences exist between spacings of contour banks designed using the CoSDT and the current sugar industry design nomograph as shown in Table 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 as shown in Table 4 and Table 5.

Table 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]

Note: [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)

One of the major sources of differences is in the *R* factor and storm flow factor which drive erosion in the USLE and sediment yield in the MUSLE respectively, as shown in Table 4. 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.

Table 4 Drivers of erosion processes in the USLE and sediment yield in the MUSLE across the four regions in the sugar industry of South Africa

Region	USLE *R* factor (MJ mm ha^{-1} h^{-1})	MUSLE storm flow factor (MJ mm ha^{-1} h^{-1})
South Coast	300	1 – 662
North Coast	300	1 – 841
Zululand and Irrigated	300	1 – 846
Midlands	300	2 – 155

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, as shown in in Table 5. 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. Stationary sugarcane cover factors are not representative of conditions in the sugar industry 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.

Table 5 Parameters from the CoSDT and the current sugar industry design nomograph

Parameter	a		b		c	
	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

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.

4 Conclusions

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 incorporating a drop down menu containing the four regions in the sugar industry in the graphical user interface. 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 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.

Therefore, 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). Much as the CoSDT was developed for the sugar industry in South Africa, the methodology may be employed in the development of a similar tool for other crops and/ or areas with similar problems.

Acknowledgements

We thank SASRI for providing a bursary to conduct this research.

References

Alexandridis, T. K., A. M. Sotiropoulou, G. Bilas, N. Karapetsas, and N. G. Silleos. 2015. The effects of seasonality in estimating the C-factor of soil erosion studies. *Land Degradation and Development,* 26(6): 596-603.

Botha, F., G. F. Buchanan, Q. V. Mann, D. McArthur, J. H. Meyer, A. W. Schumann, and R. A. Wood. 1999. *ldentification and Management of the Soils of the South African Sugar Industry.* Mount Edgecombe, RSA: SASEX.

Chen, E., and D. S. Mackay. 2004. Effects of distribution-based parameter aggregation on a spatially distributed agricultural nonpoint source pollution model. *Journal of Hydrology,* 295(1): 211-224.

D'Huyvetter, J. H. H. 1985. Determination of threshold slope percentages for the identification of arable land in Ciskei, M.S. thesis, University of Fort Hare, East London, RSA.

DAWS. 1990. Predicting raifall erosion losses. In *National Soil Conservatiuon Manual*, ed. J. F. l. G. Mathee, ch. 6, 1-12. Pretoria, RSA: Directorate of Agricultural Engineering and Water Supply.

DEFRA. 2007. Factors that influence erosion and runoff. In *Think Soils*, ed. DEFRA, ch. 2, 7-29. Bristol, UK: Environment Agency.

Gwapedza, D., A. Slaughter, D. Hughes, and S. Mantel. 2018. Regionalising MUSLE factors for application to a data-scarce catchment. In *Proceedings of the International Association of Hydrological Sciences,* 377, 19-24. Harare, Zimbabwe, 25-27 October 2018.

Krois, J., and A. Schulte. 2014. GIS-based multi-criteria evaluation to identify potential sites for soil and water conservation techniques in the Ronquillo watershed, northern Peru. Applied Geography*,* 51(7): 131-142.

Le Roux, J., T. Morgenthal, J. Malherbe, D. Pretorius, and P. Sumner. 2008. Water erosion prediction at a national scale for South Africa. *Water SA,* 34(3):305-314.

MacVicar, C. N., J. M. De Villiers, R. F. Loxton, E. Verster, J. J. N. Lambrechts, F. R. Merryweather, and H. J. V. M. Harmse. 1977. *Soil Classification. A Binomial System For South Africa.* Pretoria, RSA: Department of Agricultural Development.

Manyevere, A., P. Muchaonyerwa, P. N. S. Mnkeni, and M. C. Laker. 2016. Examination of soil and slope factors as erosion controlling variables under varying climatic conditions. *Catena,* 147(dec): 245-257.

Matthee, J. F. L. G., and C. J. Van Schalkwyk. 1984. *A Primer on Soil Conservation.* Pretoria, RSA: Department of Agriculture.

Mthembu, I., P. Lyne, C. Bezuidenhout, K. Collings, O. de Haas, D. Wilkinson, and G. W. Maher. 2011. *Mapping Land Suitability for Mechanized Harvesting in Cane Growing Areas, South Africa* (Report No. 07RE06). Mount Edgecombe, RSA: South African Sugarcane Research Institute.

Otim, D. 2020. Development of updated design norms for soil and water conservation structures in the sugar industry of South Africa. Ph.D. diss., University of KwaZulu-Natal, Pietermaritzburg, RSA.

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

Otim, D., J. C. Smithers, A. Senzanje, and R. Van Antwerpen. 2020. Verification of runoff volume, peak discharge and sediment yield simulated using the ACRU model for bare fallow and sugarcane fields. *Water SA,* 46(2): 182-196.

Palmer, T., and A. Ainslie. 2006. *Country Pasture/Forage Resource Profiles-South Africa.* Rome, Italy: FAO.

Platford, G. G. 1987. A new approach to designing the widths of panels in sugarcane fields. In *Proc. of the South African Sugar Technologists' Association*, 150-155. Mount Edgecombe, RSA, June.

Reinders, F. B., H. Oosthuizen, A. Senzanje, J. C. Smithers, R. J. Van der Merwe, I. Van der Stoep, and L. Van Rensburg. 2016. *Development of Technical and Financial Norms and Standards for Drainage of Irrigated Lands* (Report No. TT 655/15). Pretoria, RSA: Water Research Commission.

Renard, K. G., G. R. Foster, G. A. Weesies, and J. P. Porter. 1991. RUSLE: Revised universal soil loss equation. *Journal of Soil and Water Conservation,* 46(1): 30-33.

Russell, W. B. 1994. *CEDARA Report: Standards and Norms for Soil and Water Conservation Planning in Kwazulu-Natal* (Report No. N/A/93/32). Pietermaritzburg, RSA: KwaZulu-Natal Department of Agriculture.

SASA. 2002. *Standards and Guidelines for Conservation and Environmental Management in the South African Sugar Industry.* Mount Edgecombe, RSA: South African Sugar Association.

SASA. 2016. *South African Sugar Industry Directory 2016/2017.* Mount Edgecombe, RSA: SASA.

SASA. 2018a. Weather Web. Availble at: http://portal.sasa.org.za/weatherweb/weatherweb.ww_menus.menu_frame?menuid=1. Accessed 24 May 2018.

SASA. 2018b. Where To Find Us. Availble at: http://www.sasa.org.za/Libraries/Maps/Map_of_Operational_Areas.sflb.ashx. Accessed 24 May 2018.

SASRI. 2011. *South African Sugar Industry Visitors' Guide.* Mount Edgecombe, RSA: SASRI.

SASRI. 2016. *SASRI InfoPack.* Mount Edgecombe, RSA: South African Sugarcane Research Institute.

Schmidt, E. J., R. E. Schulze, and M. C. Dent. 1987. *Flood Volume and Peak Discharge from Small Catchments in Southern Africa Based on the SCS Technique* (Report No. TT 31/87.). Pretoria, RSA: Water Research Comission.

Schulze, R. E. 1995a. Sediment yield. In *Hydrology and Agrohydrology: A Text to Accompany the ACRU 3.00 Agrohydrological Modelling System*, ed. S. A. Lorentz and R. E. Schulze, ch. 16, 1-34. Pietermaritzburg, RSA: Department of Agricultural Engineering, University of Natal.

Schulze, R. E. 1995b. Streamflow. In *Hydrology and Agrohydrology: A Text to Accompany the ACRU 3.00 Agrohydrological Modelling System*, ed. R. E. Schulze, ch. 10, 1-7. Pietermaritzburg, RSA: Department of Agricultural Engineering, University of Natal.

Schulze, R. E. 1975. Catchment evapotranspiration in the Natal Drakensberg. Ph.D. diss., University of Natal, Pietermaritzburg, RSA.

Schulze, R. E. 2011. *A 2011 Perspective on Climate Change and the South African Water Sector* (Report No. 1843/2/11). Pretoria, RSA: Water Research Comission.

Schulze, R. E. 2013. *Modelling Impacts of Land Use on Hydrological Responses in South Africa with the ACRU Model by Sub-delineation of Quinary Catchments into Land Use Dependent Hydrological Response Units* (Internal report). Pietermaritzburg, RSA: Centre for Water Resources Research, University of KwaZulu-Natal.

Schulze, R. E., G. R. Angus, S. D. Lynch, and J. C. Smithers. 1995. ACRU: Concepts and structure. In *Hydrology and Agrohydrology: A Text to Accompany the ACRU 3.00 Agrohydrological Modelling System*, ed. R. E. Schulze, ch. 2, 1-26. Pietermaritzburg, RSA: Department of Agricultural Engineering, University of Natal.

Schulze, R. E., and N. Davis. 2018. Personal communication with author. Pietermaritzburg, RSA, 28 August.

Schulze, R. E., and R. P. Kunz. 2010. Climate change 2010 and sugarcane production. In *Atlas of Climate Change and the South African Agricultural Sector: A 2010 Perspective*, ed. R. E. Schulze, ch. 5.5, 191-206. Pretoria, RSA: Department of Agriculture, Forestry and Fisheries.

Schulze, R. E., B. C. Hewitson, K. R. Barichievy, M. A. Tadross, R. P. Kunz, M. J. C. Horan, and T. G. Lumsden. 2011. *Methodological Approaches to Assessing Eco-Hydrological Responses to Climate Change in South Africa* (WRC Report No. 1562/1/10). Pretoria, RSA: Water Research Commission.

Schulze, R. E., and E. J. Schmidt. 1995. Peak discharge. In *Hydrology and Agrohydrology: A Text to Accompany the ACRU 3.00 Agrohydrological Modelling System*, ed. R. E. Schulze, ch. 12, 1-11. Pietermaritzburg, RSA: Department of Agricultural Engineering, University of Natal.

Schulze, R. E., E. J. Schmidt, and J. C. Smithers. 2004. *Visual SCS – SA User Manual Version 1.0: PC Based SCS Design Flood Estimates for Small Catchments in Southern Africa* (ACRUcons Report No. 52). Pietermaritzburg, RSA: School of Bioresources Engineering and Environmental Hydrology, University of KwaZulu-Natal.

Shih, H. M., and Yang, C. T. 2009. Estimating overland flow erosion capacity using unit stream power. *International Journal of Sediment Research,* 24(1): 46-62.

Smithers, J., and R. Schulze. 1995. *ACRU Agrohydrological Modelling System User Manual.* Pietermaritzburg, RSA: Department of Agricultural Engineering, University of Natal.

Smithers, J. C., P. Mathews, and R. E. Schulze. 1996. *The Simulation of Runoff and Sediment Yield from Catchments under Sugarcane Production at La Mercy* (ACRUcons Report No. 13). Pietermaritzburg, RSA: Department of Agricultural Engineering, University of Natal.

Smithers, J. C., R. E Schulze, N. L. Lecler, S. W. Kienzle, S. A. Lorentz, and R. P. Kunz. 1995. User guidelines for setting up information. In *ACRU Agrohydrological Modelling System: User Manual Version 3.00*, ed. R. E. Schulze and J. C. Smithers, ch. 6, 1-190. Pietermaritzburg, RSA: Department of Agricultural Engineering, University of Natal.

Tanyaş, H., Ç. Kolat, and M. L. Süzen. 2015. A new approach to estimate cover-management factor of RUSLE and validation of RUSLE model in the watershed of Kartalkaya Dam. *Journal of Hydrology*, 528(Sep): 584-598.

Van Antwerpen, R., 2019. *Personal Communication with Author*. Mount Edgecombe, RSA: Mount Edgecombe.

Van Staden, H., and A. A. Smithen. 1989. Protection of cultivated lands. In *National Soil Conservation Manual*, ed. J. F. l. G. Mathee, ch. 8, 8.3-1-8.3-44. Pretoria, RSA: Directorate of Agricultural Engineering and Water Supply.

Williams, J., and H. Berndt. 1977. Sediment yield prediction based on watershed hydrology. *Transactions of the ASAE,* 20(6): 1100-1104.

Williams, J. R. 1975. Sediment-yield prediction with universal equation using runoff energy factor. *Present and Prospective Technology for Predicting Sediment Yields and Sources*, 40: 244-252.

Williams, J. R., and J. G. Arnold. 1997. A system of erosion—sediment yield models. *Soil Technology,* 11(1): 43-55.

Wischmeier, W. H., and D. D. Smith. 1965. *Rainfall Erosion Losses From Cropland East Of The Rocky Mountains: Guide For Selection Of Practices For Soil And Water Conservation.* Washington D.C., USA: USDA.

Wischmeier, W. H., and D. D. Smith. 1978. *Predicting Rainfall Erosion Losses-A Guide to Conservation Planning.* Washington D.C., USA: USDA.