FURTHER DEVELOPMENT, UPDATING AND ASSESSMENT OF THE SCS-SA MODEL FOR DESIGN FLOOD ESTIMATION IN SOUTH AFRICA USING A CONTINUOUS SIMULATION APPROACH

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ABSTRACT

The occurrence of flood events, of extreme magnitude, are increasing in South Africa (SA). These events may lead to the possible loss of lives and significant financial losses. Design Flood Estimation (DFE), i.e. the flood magnitude related to a specified return period or probability of exceedance, is required for the design of hydraulic structures. Many of the popular DFE methods, that are presently utilised in SA, were developed in the 20th century, therefore, they require to be updated. New and innovative local and international techniques and decades of supplementary rainfall and runoff data are available to update the outmoded DFE methods that are presently used in SA. The South African adaptation of the Soil Conservation Service (SCS-SA) model is a widely used, rainfall-runoff, method for estimating design floods on small catchments (< 30 km^2). When the SCS Curve Number (CN) model was adapted for use in SA, there was limited rainfall data, and computing power, available. Consequently, the SCS-CN model has received substantial attention from researchers in SA and internationally. Congruently, continuous simulation modelling has been proposed to surmount the major restrictions of event-based models, such as the SCS-SA model. A review of the literature indicated that the SCS-SA model could be updated, using a continuous simulation modelling approach. Longer rainfall records, that are currently available, could be used to simulate long periods of runoff, which could be used to estimate design floods and antecedent soil moisture which could be used to improve the simulated hydrological responses from the SCS-SA model. Within the SCS-SA model, antecedent moisture conditions have a substantial impact on the estimation of stormflow depths. However, it may be possible to use a continuous simulation modelling approach to update the antecedent soil moisture adjustment procedures of the SCS-SA method. In addition, the long periods of observed and simulated rainfall-runoff data, that are available, could be used to verify popular CN derivation techniques. Thereafter, a suitable CN derivation technique may be used to calculate CNs, specifically for South African landcover and soil classes, if needed. This document contains a brief review of the SCS-CN model as well as possible CN derivation techniques and methods to account for antecedent soil moisture conditions when using the SCS-SA model for DFE.

TABLE OF CONTENTS

Page

LIST OF FIGURES

Page

LIST OF TABLES

Page

LIST OF ABBREVIATIONS

ΔS	Index of change in catchment soil moisture storage
ACRU	*Agricultural Catchments Research Unit*
AM	Annual Maximum
AMC	Antecedent Moisture Conditions
AMC_{II}	Average Antecedent Moisture Conditions
c	Coefficient of Initial Abstraction
CN	Curve Number
CN_f	Final Curve Number
CN_I or CN_{III}	Adjusted CN
CN_{II}	Median or “Average” CN
CS	Continuous Simulation
D	Drainage
DFE	Design Flood Estimation
ET	Evapotranspiration
F	Quantity of actual infiltration
GIS	Geographic Information Systems
GTI	*GEOTERRAIMAGE*
HSG	Hydrological Soil Group
Ia	Initial abstraction
JAM	Joint Association Method

KCC	Koppen Climate Classification
LULC	Land Use and Land Cover
MAP	Mean Annual Precipitation
MCM	Median Condition Method
NLC	National Land Cover
NRCS-CN	Natural Resource Conservation Service Curve Number
P	Rainfall depth
Pe	Probability of Exceedance
P_s	Threshold-Rainfall
Q	Actual direct surface runoff
RP	Return Period
RS	Remote Sensing
S	Potential maximum soil water retention
SA	South Africa
SCS	Soil Conservation Service
SM	Soil Moisture
SMA	Soil Moisture Accounting
SMI	Soil Moisture Index
SMS	Soil Moisture Status
TU	Terrain Unit
USA	United States of America

USDA	United States Department of Agriculture
V_o	SM store level at the commencement of a rainfall event

1. INTRODUCTION

Surface runoff was defined by Tsheko (2006) as the proportion of precipitation that enters stream channels or water bodies, as surface or subsurface flow, when the rate at which the water infiltrates the soil is less than the rate of precipitation. Fang and Pomeroy (2016) described a flood as a teeming volume of water that inundates areas that are usually dry and Ravazzani *et al.* (2007) explicitly stated that floods are the worst natural hazards that cause injury, deaths and unwarranted damage to property. Smithers (2012) reported that the consequences of climate change include more frequent, unpredictable and intense precipitation events. As a result of this, there will be an increasing number of climate-related hazards, like floods (Kusangaya *et al.*, 2014). The severity of flood events are aggravated by local problems such as increasing populations residing on floodplains, and increased runoff from hard, impermeable surfaces (Douglas *et al.*, 2008). It has been emphasised by Cameron *et al.* (1999) and Healy (2000) that reliable, accurate estimates of floods are essential for the proper design of hydraulic structures. It is, therefore, vital to update and improve DFE techniques and models in an effort to limit the destruction caused by extreme events that are likely to occur in the future (Smithers, 2012).

DFE associates the magnitude of a flood with a Probability of Exceedance (Pe), or Return Period (RP), to assess a flood risk (Smithers, 2012; Kang *et al.*, 2013). Chetty (2010) reported that there are many DFE techniques available, but the accessibility of hydrological data has an impact on the application of the aforementioned techniques. Chetty (2010) also pointed out that extensive, good quality runoff records are uncommon in SA, however, good quality daily rainfall data with an acceptable record length do exist. Consequently, rainfall data are commonly used as an input to rainfall-runoff methods for DFE (Smithers and Schulze, 2002). These methods usually consist of event-based modelling and Continuous Simulation (CS) modelling approaches to DFE (Smithers and Schulze, 2002; Chetty, 2010).

Event-based models are used more frequently, due to the simplicity of these models, since all the processes that are necessary for a CS model do not need to be represented in an event-based model (Berthet *et al.*, 2009). An added advantage of event-based models are the minimal data requirements, hence, these model could be easily used and implemented (Berthet *et al.*, 2009). The SCS-CN model is a popular event-based model, used globally for DFE, and it forms the foundation for various other runoff models (Harbor, 1994; Hawkins *et al.*, 2009; Aichele and Andresen, 2013). According to Schulze and Schmidt (1987), in the SCS-CN model, the runoff depth is calculated using a rainfall depth and a parameter called the CN. The CN may be described as an index of a catchments runoff response characteristics (Schulze and Arnold, 1979). However, event-based methods have numerous shortcomings such as the simplifying supposition that the T-year RP rainfall results in the T-year RP runoff (Rahman *et al.*, 1998; Cameron *et al.*, 1999; Smithers, 2012).

CS modelling has been proposed to overcome the limitations of event-based modelling (Calver and Lamb, 1995; Cameron *et al.*, 1999; Smithers and Schulze, 2002; Smithers, 2012; Rowe, 2015). Rowe (2015) made reference to work done by Schulze (1989) and Smithers and Schulze (2002), which indicated that the Pe of floods, generated using CS models, are usually not associated to the Pe of rainfall, as assumed in simple event-based models. Blazkova and Beven (2002) reported that CS models use widely available observed historical rainfall data, or stochastically generated rainfall series, as an input, and a frequency analysis of the hydrological responses, that are simulated, could be used for DFE. CS modelling has also been recommended to modellers for many years as a method to estimate initial catchment conditions (Berthet *et al.*, 2009). The application of the SCS-CN method together with CS models has been used extensively in rainfall-runoff modelling (Hawkins et al., 2010).

According to Chetty (2010), DFE practices in SA generally rely on event-based methods and experimental formulae, that were developed in the early 1970s, and had minor or no consequent updates. In the late 1970s and 1980s the SCS-CN method was adapted for use in South Africa (Schulze and Arnold, 1979; Schulze and Schmidt, 1984; Dunsmore *et al.*, 1986; Schulze and Schmidt, 1987), but with modern computers, improved computing power, and longer rainfall records, the SCS-SA method could be refined and updated to integrate the new data and techniques that are presently available (Smithers and Schulze, 2002).

The specific objectives of this study are to: (a) briefly review two rainfall-runoff approaches that are used to estimate runoff, (b) highlight methods, that are used in SA and internationally, to derive CNs and account for antecedent catchment moisture conditions, (c) propose a methodology to derive CNs based on South African land cover and soil type classifications, (d) update the SCS-SA soil moisture adjustment procedures using results from the CS model under development (Rowe, 2019) and (e) develop a refined and updated version of the SCS-SA model using the results and methodology from the CS model that is currently being developed (Rowe, 2019).

2. RAINFALL-RUNOFF MODELLING APPROACHES FOR DFE

In this chapter, two rainfall-runoff approaches, for DFE, that are used in SA are reviewed. Rainfall-runoff methods for DFE could be split into two comprehensive categories, i.e. event-based and CS approaches (Hoes and Nelen, 2005). Only the SCS-SA and *Agricultural Catchments Research Unit* (*ACRU*) models will be discussed, in this chapter, because these two models are commonly used in SA (Schulze *et al.*, 1992; Schulze *et al.*, 2004; Chetty, 2010).

2.1 Event-Based Modelling

Design-event models are widely used because they are easy to apply and they lump heterogenous and intricate catchment processes into a single process (Smithers and Schulze, 2002). In the opinion of Cameron *et al.* (1999), the design event approach generally assumes that it is possible to identify the storm profile depth, duration and antecedent wetness that results in a hydrograph with a peak of a given RP. The SCS-SA model is a commonly used event-based rainfall-runoff method for DFE in Southern Africa (Schulze *et al.*, 1992; Smithers, 2012). However, the event-based approaches that are commonly used for DFE have several limitations (Smithers *et al.*, 2013), such as the procedures that are used to estimate Antecedent Moisture Conditions (AMC) and the restrictive assumption that the design rainfall and runoff have the same Pe, and hence the same RPs. Numerous studies have indicated that the Soil Moisture (SM), prior to stormflow producing rainfall, plays a vital role in determining the magnitude of the resulting runoff (Hawkins, 1978; Dunsmore *et al.*, 1986; Schulze and Schmidt, 1987; Mishra *et al.*, 2003; Santikari and Murdoch, 2019). Furthermore, when AMC are not taken into account, it may result in unrealistic estimates of runoff (Hawkins, 1978; Dunsmore *et al.*, 1986; Schulze and Schmidt, 1987). Pathiraja *et al.* (2012) indicated that the use of CS models are rapidly becoming a reasonable and practical substitute for the conventional event-based methods for rainfall-runoff simulation. The use of CS modelling for DFE would eliminate some of the limitations that are inherent in event-based models (Calver and Lamb, 1995; Cameron *et al.*, 1999; Smithers and Schulze, 2002; Smithers, 2012; Rowe, 2015).

2.2 CS Models

Research by Blazkova and Beven (2002), highlighted that CS models which use widely available rainfall data as an input are a practical method for DFE. Both Rahman *et al.* (1998)

and Smithers and Schulze (2002) agreed that CS models try to characterize the main processes that convert rainfall into runoff. These models are also capable of generating outflow hydrographs, using historical rainfall data or stochastic rainfall series as an input, over long time periods (Rowe, 2015). The Pe of floods, generated using CS models, are usually not related to the Pe of rainfall, as assumed in simplistic event-based models (Schulze, 1989; Smithers and Schulze, 2002). A major advantage of CS modelling is that the moisture status of the catchment, preceding flood-producing rainfall, is implicitly integrated within the modelling framework (Pathiraja *et al.*, 2012). Consequently, more realistic runoff responses are obtained when a CS modelling approach is adopted (Smithers *et al.*, 2013). A study by Smithers *et al.* (2013), evaluated the *ACRU* model on the Thukela catchment in SA, and the research concluded that the *ACRU* model could be successfully used as a CS model to simulate hydrological responses, such as runoff volumes and peak discharges, that occur on a catchment.

The *ACRU* model is a physical, conceptual CS model that is operated on a daily time increment (Schulze, 1995). An advantage of using *ACRU* for DFE is that Land Use and Land Cover (LULC) changes, that are anticipated, may be input into the model to generate design flows for present and future LULC conditions (Smithers *et al.*, 2013). The *ACRU* model was originally developed for agricultural applications (Tarboton and R E Schulze, 1992; Schulze, 1995) and it uses land cover, soil characteristics and rainfall as an input (Schulze, 1995) to a modified SCS-CN method to simulate runoff where the daily SM deficit is used to replace the CN. *ACRU* has a multi-layer daily soil water budgeting technique that can generate various outputs, such as the daily stormflow and baseflow. In the *ACRU* model, the SM deficit in the topsoil and subsoil are simulated continuously on a daily basis (Schulze, 1995; Rowe, 2015). According to Rowe (2015), this is an improvement compared to the Joint Association Method (JAM) and Median Condition Method (MCM) that are used by the SCS-SA model to account for AMC. Rowe (2019) provides an in-depth explanation on the use of the *ACRU* model to develop an improved CS modelling system for SA. The next chapter contains a comprehensive review of the SCS-CN model and Chapters 4 and 5 highlight various studies that integrated the SCS-CN model with a CS modelling approach.

3. A REVIEW OF THE SCS-CN METHOD

This chapter focuses on the evolution of the SCS-SA model, from the original SCS-CN model. The major components and limitations of the model are also highlighted in this chapter.

3.1 Background and Evolution of the SCS-SA Model

The SCS-CN method, now renamed the Natural Resource Conservation Service CN (NRCS-CN) method, was developed in 1954 for conditions dominant in the United States of America (USA) (Rezaei-Sadr and Sharifi, 2018). For consistency, the name SCS-CN model will be used in this document. The CN is a dimensionless parameter that ranges between 0 to 100 and three major physiographic characteristics of a catchment are accounted for by the CN (Schulze and Arnold, 1979; Mishra and Singh, 2003). These characteristics are represented by means of classes of LULC and soil characteristics (Savvidou *et al.*, 2016). The SCS runoff equation, which became popular in the late 1950s, was a result of approximately 20 years of studies, based on rainfall-runoff relationships, that were carried out on small, agricultural catchments located in the USA (Mishra and Singh, 2003; Mishra *et al.*, 2007). Subsequently, the model had been adapted, verified and used in various other countries. The use of the SCS-CN technique, for southern African conditions, was first proposed by Reich (1962) nearly 60 years ago. However, the method only gained popularity after the SCS user manual, with specific Southern African input information, was published in 1979 (Schulze and Arnold, 1979).

A significant amount of research effort had been expended, in the Department of Agricultural Engineering at the University of KwaZulu-Natal, at adapting the SCS-CN method and improving the simulation of runoff volumes and peak discharges for conditions in SA. The rainfall for a given RP was treated as a constant and the remaining input variables of the SCS-CN equation were considered to be random variables, by Haan and Schulze (1987), to appropriately convert a rainfall value with a given Pe to a runoff value with the same Pe. The study by Haan and Schulze (1987), also indicated that the original SCS-CN method to account for AMC resulted in practical, sensible approximations of runoff depths. Schulze and Arnold (1979) and Schulze and Schmidt (1987) worked on adapting and refining the SCS-CN method, to develop the SCS-SA method specifically for application in Southern Africa. The SCS-SA method was computerised and is extensively used for DFE on small catchments (<30 km^2) in southern Africa (Schulze *et al.*, 1992; Schulze *et al.*, 2004).

The importance of the relationship between the AMC, of a catchment, and runoff has been emphasized in various sources of literature (Schulze and Arnold, 1979; Dunsmore *et al.*, 1986; Schulze and Schmidt, 1987; Mishra and Singh, 2003). The original SCS-CN method used the 5-day antecedent rainfall as an antecedent precipitation index of AMC (Mishra and Singh, 2003). The relationship between CNs and AMC was later expressed, by Hawkins (1978), as a continuum rather than discrete steps. In the SCS-SA model, the MCM takes regional differences in median SM conditions prior to extreme rainfall events into account and the JAM takes the joint association between rainfall, runoff and AMC into consideration (Schulze and Schmidt, 1987). The procedures that were used, by other researchers, to derive CNs and account for AMC, when using the SCS-CN model, will be discussed in more detail in Chapters 4 and 5 respectively.

3.2 Components of the SCS-CN Method

The SCS-CN stormflow, or runoff, equation is a simple algebraic formula that relates a stormflow depth to a CN and total rainfall depth (P). For stormflow to occur, the rainfall must satisfy the initial abstractions (Ia), which consist of depression storage, interception and infiltration into the soil prior to the commencement of stormflow. Once the stormflow begins, the quantity of actual infiltration (F) increases with increasing rainfall up to the potential maximum soil water retention (S). The actual direct surface runoff (Q) also increases with rainfall. The connection between these variables, for a constant rainfall intensity event, are illustrated in Figure 3.1 (Schulze and Arnold, 1979).

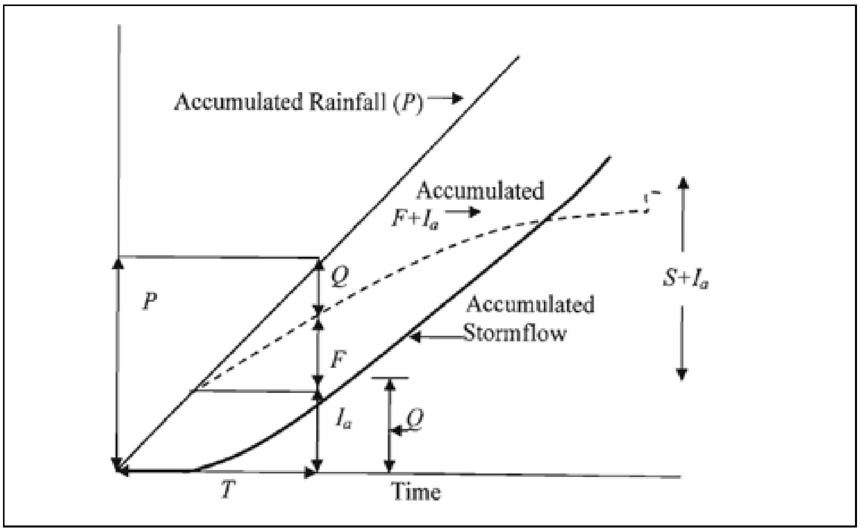

Figure 3.1 A schematic representation of the relationships that were used to derive the SCS-CN stormflow equation (Schulze and Arnold, 1979)

3.2.1 The SCS-CN stormflow equation

The original SCS-CN method was based on a combination of the water balance equation and the proportionality equality and Ia-S hypotheses as shown by Equations 3.1-3.3 (Schulze and Arnold, 1979; Mishra and Singh, 2003; Jain *et al.*, 2006):

(a) The water balance equation:

$$P = Ia + F + Q \tag{3.1}$$

(b) The proportionality equality hypothesis:

$$\frac{Q}{P - Ia} = \frac{F}{S} \quad \text{(3.2), and}$$

(c) Ia-S hypothesis:

$$Ia = c \times S \tag{3.3}$$

where

c = coefficient of initial abstraction (dimensionless).

The above three relationships were used to derive the SCS-CN stormflow equation (Schulze and Arnold, 1979; Mishra and Singh, 2003):

$$Q = \frac{(P - I_a)^2}{(P - I_a + S)} \tag{3.4}$$

The limits of Equation (3.4) are that when $P \geq cS$ then $Q > 0$, otherwise $Q = 0$ (Schulze and Arnold, 1979). The CN values may be obtained using look-up tables that have been published by various sources (NEH, 1959; Schulze and Arnold, 1979; Schulze and Schmidt, 1987; Schulze *et al.*, 2004). The CN may then be used to calculate S (Schulze and Arnold, 1979):

$$S = \frac{25400}{CN} - 254 \tag{3.5}$$

3.2.2 Important variables and components that influence runoff generation when using the SCS-CN model

According to Schulze (1984) soils play a vital role in the estimation of stormflow peaks and volumes. The original SCS Hydrological Soil Group (HSG) classification consists of four lettered groups (A, B, C and D) (Schulze and Arnold, 1979). All the surveyed soils were assigned an HSG which ranges from the lowest runoff potential (A) to the highest runoff potential (D). However, South African soils display a wide spectrum of properties. Therefore, three intermediate soil groups (A/B, B/C and C/D) were used in the classification of soil forms and series that are used by the SCS-SA model (Schulze and Arnold, 1979). The S parameter, in the CN method, is an indication of the capability of the soil to store infiltrated water and may be calculated using Equation (3.5 (Schulze and Schmidt, 1987; Kim *et al.*, 2018). When using the SCS-CN procedure, the consequences of the surface conditions of a specific catchment are estimated by evaluating the land use, stormflow potential, land cover and land treatment (Schulze *et al.*, 1992; Ghile, 2004). According to Ngcofe and Thompson (2015), the land cover may be described as the physical material on the surface of the earth, whereas land use is an indication of how a particular land cover is utilised by humans. Landcover information is generally used to derive physical properties of the catchment, such as the CN. Research by Wehmeyer *et al.* (2011), in Iowa in the USA, indicated that urbanisation and deforestation resulted in an increase in the CN due to the land cover change. A study carried out by Rietz and Hawkins (2000) indicated that land use had a significant impact on the CN value. A study by Deshmukh *et al.* (2013) in the Narmada catchment, in India, indicated that an increase in agricultural areas resulted in an increase in the CN over time. The Coefficient of Ia (c) was defined to include all the rainfall that occurred prior to the commencement of surface runoff, or stormflow (Schulze and Arnold, 1979). Schulze and Arnold (1979) reported that the United States Department of Agriculture (USDA) found the c to be 0.2 by regression of Ia on S (Schulze and Arnold, 1979). However, based on research carried out by Schulze and Schmidt (1987), it was evident that a c value of 0.2 was too high, for small to medium storms in SA. Therefore, a c value of 0.1 was adopted for use in SA (Schulze and Schmidt, 1987).

3.3 Importance of the CN and AMC

The SCS-CN method integrates four main factors, that have an impact on runoff generation i.e. land cover, land use and treatment, soil type and AMC, into a single parameter called the CN (Rezaei-Sadr and Sharifi, 2018). The CN values range from 0 (no runoff produced from rainfall) to 100 (all rainfall is converted to runoff for every rainfall event) (Hawkins *et al.*, 2010). According to Mishra *et al.* (2007), an accurate CN determination is one of the most important factors in the SCS-CN methodology. An accurate CN value results in an accurate estimation of runoff, therefore, it has been highlighted by Mishra *et al.* (2007) that the calculated runoff is more sensitive to the CN than to the rainfall depth. However, according to Schulze and Schmidt (1987), second to storm rainfall, the stormflow depth is essentially a function of AMC. Approximately 10% of the CN variation is caused by differences in AMC that arise from changing land and soil conditions over time (Mishra *et al.*, 2007). A study done, in Arizona, USA, by Zhang *et al.* (2011) reported an average change of 0.05 mm in runoff for every 1% change in SM. Both Zhang *et al.* (2011) and Sakazume *et al.* (2015) indicated that there is a strong relationship between runoff and the AMC of a catchment.

3.4 Limitations of the SCS-CN Model

The majority of the files and supporting data that were used to develop the SCS-CN method, in 1954, had not been published (Mishra and Singh, 2003; Hawkins *et al.*, 2009). Consequently, the CN method did not undergo critical review after it was made available for use (Hawkins *et al.*, 2009; Woodward, 2017). The perceived disadvantages of the SCS-CN method, according to Ponce and Hawkins (1996) and Bansode and Patil (2014), are the model's marked sensitivity to the CN and the absence of clear direction on how to change antecedent conditions. According to Gonzalez *et al.* (2015), hydrological processes are impacted by various other surface parameters that are dynamic and vary spatially and temporally. Gonzalez *et al.* (2015) argued that the SCS-CN model would perform better if these additional dynamic parameters, such as soil infiltration characteristics and vegetation growth, are accounted for when determining the CN. According to Smithers and Schulze (2002), the SCS-SA model is highly sensitive to the assumed AMC. The method that is used to account for the joint association between rainfall, runoff and AMC (Schulze and Schmidt, 1987), only includes events that are equivalent to or less than the 20-year RP. Smithers and Schulze (2002) indicated that this could be improved using the currently available databases, of longer record, and enhanced computing power. Another limitation of the JAM is that the method can only be applied when the initial or Average CN (CN_{II}) lies between 50 and 90 (Schulze *et al.*, 2004). The computations for the JAM method were based on rainfall extremes for selected rainfall stations within each of the 712 hydrological zones in SA, therefore, there is no flexibility to choose an alternative rainfall station within a specific zone when using this method (Schulze *et al.*, 2004). When using the MCM to account for typical AMC, the stormflow is only computed for the most commonly occurring AMC of an area and not the actual AMC (Schulze *et al.*, 2004). However, Smithers and Schulze (2002) indicated that the MCM could be re-evaluated and possibly improved by the use of CS modelling. The SCS-SA method was also deemed to be inconsistent, by Smithers and Schulze (2002), because of the procedure to select a relevant CN. Chapter 4 focuses on the popular methods that are used to calculate CNs.

4. THE DERIVATION OF CURVE NUMBERS

This chapter provides details on methods, that are available, to derive CNs. The last section of this chapter focuses on the use of a map, to represent CNs, based on the landcover and HSG of an area.

4.1 The Determination of Median CNs Using Annual Maximum Flood Data

Both Schulze and Schmidt (1987) and Mishra and Singh (2003) reported that in most cases the SCS used infiltrometer tests and rainfall-runoff records, that corresponded to maximum annual flows from gauged catchments, to compute CNs. The catchments that were in the USA had a single soil cover and soil group, in most situations, and the catchment sizes ranged between 0.0971 ha to 18 650 ha (Woodward *et al.*, 2002; Hawkins *et al.*, 2009; Tedela *et al.*, 2011). Unfortunately, most of the original information that was used for deriving CNs were not preserved (Woodward *et al.*, 2002; Hawkins *et al.*, 2009). The CN for a single soil and land cover condition was derived using the largest annual storm runoff and the associated rainfall (Woodward *et al.*, 2002; Hawkins *et al.*, 2009). The natural, unordered, P-Q data were then plotted on arithmetic paper that contained an array of different CNs, as illustrated in Figure 4.1 (Hawkins *et al.*, 2009). A more detailed CN array, that corresponded to a range of P-Q values, is provided in Appendix A.

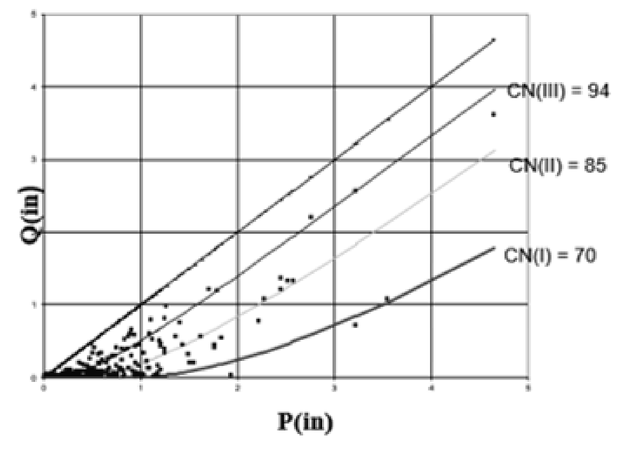

Figure 4.1 A graph of the CN array that was constructed, at the same scale, and laid over the observed P-Q plots to derive CNs (Woodward et al., 2002)

The CN line, from the CN array, that had an equal number of data points on either side of the line was then selected as the median, or "average", CN (CN_{II}) for the catchment (Schulze and

Schmidt, 1987; Woodward *et al.*, 2002). These CN_{II} values are associated with Average AMC (AMC_{II}) (Schulze and Schmidt, 1987). The same procedure was followed for various other soil-land cover complexes. However, not all land cover, soils and hydrologic conditions were represented by observed P-Q data (Schulze and Schmidt, 1987). Therefore, the CNs for these conditions were obtained by interpolation to complete the CN tables (Mishra and Singh, 2003). If data from a soil-landcover complex were available from more than one site, the CN_{II} values, from each site were averaged to obtain a CN representative of that specific soil-landcover complex (Woodward *et al.*, 2002). The natural scatter, that was displayed by the plotted points, was used to approximate the upper-and-lower enveloping CN conditions that were above or below the CN_{II} (Schulze and Schmidt, 1987; Woodward *et al.*, 2002; Mishra and Singh, 2003). Figure 4.1 contains the CN_{I} (dry catchment conditions) and CN_{III} (wet catchment conditions) lines that envelope the CN_{II} line.

4.2 CN Derivation Using Observed, or Simulated, Natural P-Q Data

According to Bonta (1997), CNs were derived from observed P-Q data, however, there is no standard technique that is used to derive CNs. The original method used Annual Maximum (AM) floods to derive CNs. However, observed or simulated, unordered, or natural, P-Q data could be used to derive CNs. Solving for S, Equation (3.4 may be rewritten as follows (Schulze and Schmidt, 1987):

$$S = \frac{(1 - c)Q + 2cP - \sqrt{(c^2 - 2c + 1)Q^2 + 4cPQ}}{2c^2} \tag{4.1}$$

Equation (4.1 may be used to determine the appropriate S, and hence CN, values using observed or simulated P-Q data. Solving for CN, Equation (3.5 may be rewritten as follows (Schulze and Schmidt, 1987):

$$CN = \frac{25400}{S + 254} \tag{4.2}$$

The CN at which Q commences for a given P should be calculated using the following equation (Hawkins *et al.*, 2009; D'Asaro *et al.*, 2014):

$$CN_0 = \frac{25400}{\frac{P}{c} + 254} \tag{4.3}$$

where

CN_0 = CN at P = Ia, when Q = 0 (dimensionless).

Tedela *et al.* (2011) defined a series of AM events, based on the AM peak flow rate and volume to derive the geometric mean CN for ten catchments in the eastern USA. Firstly, the S value was calculated using Equation(4.1. Thereafter, the geometric mean CN was calculated using the following equation:

$$\mathrm{CN} = \frac{100}{1 + \frac{10^{\log \mathrm{S}}}{254}} \qquad (4.4)$$

The results from the study by Tedela *et al.* (2011) showed that the geometric mean CN, that was derived using Equation (4.4, provided locally consistent CN estimates with a probabilistic basis (Tedela *et al.*, 2011).

4.3 Transforming Frequency Distributions to Derive CNs

Hjelmfelt (1983) proposed the concept of frequency matching data points to derive CNs. Equation (3.4) was originally developed to determine a runoff depth from a rainfall depth of a given RP (Schulze and Schmidt, 1987). Therefore, on a catchment where observed runoff data are available, the AM series of daily stormflow could be determined using the observed stormflow records. On small catchments, the stormflow depth may be taken to be approximately equal to the total runoff depth for the AM day's flow (Schulze and Schmidt, 1987). An estimate of the expected maximum one-day runoff depth with a given risk of exceedance may be generated using a line fitted, by eye (for e.g. the Weibull distribution), to the plotted points of the AM series. Alternatively, a numerical computation of extreme value depths following standard statistical procedures may be used. Similarly, the AM series, for the same years of record, may be used to define the one-day rainfall depth for the same risk of exceedance. Equation (4.1 may then be used to compute S, which may then be substituted into Equation (4.2 to calculate the CN. The CN, which may vary slightly with RP, may then be taken to be the representative CN for the catchment. However, this method should only be applied when a sufficient record length, of data, is available to fit extreme value distributions with confidence (Schulze and Schmidt, 1987). However, there is an apparent relationship between the CN and the causative rainfall depth (Hawkins, 1993; Hawkins *et al.*, 2009). The next section of this chapter focuses on a technique that is used to derive CNs which are dependent on the causative rainfall depths.

4.4 CN Derivation Using Asymptotic Functions

The asymptotic approach uses all the years of recorded P-Q data to derive CNs as a function of rainfall depth. This approach may be used with natural or ordered data, however, when ordered data are used, the catchment behaviour is easily identified because the plotted points display less scatter (Hawkins *et al.*, 2009). Therefore, the data are arranged, or ordered, in ascending order. The P-Q depths are first sorted independently, thereafter, the data are realigned on a rank-order basis to form P-Q pairs that have the same RPs (Banasik and Woodward, 2010). Therefore, in the ordered dataset a Q-value may not correspond to the rainfall event that resulted in the runoff. The 'asymptotic CN', calculated for each P–Q ordered pair, is then plotted as a function of the corresponding rainfall depth (Gonzalez *et al.*, 2015). It was highlighted by Hawkins (1993) that if the rainfall amount is increasing, the CNs calculated using Equation (4.2, will approach a nearly constant value. Therefore, a typical asymptote is obtained, as the rainfall depth increases. According to Hawkins (1993), the resulting CN–P plots generally exhibit three unique patterns, namely, the standard, complacent and violent behaviour.

4.4.1 Standard catchment behaviour

From the observed plots (T series in Figure 4.2), the characteristics of the standard behaviour were noted when the CN decreases as the rainfall depth increases (Hawkins, 1993; Hawkins *et al.*, 2009; Hawkins *et al.*, 2015; Woodward, 2017). However, the CN approaches an almost constant value, termed CN_∞, for larger storms (Hawkins, 1993; Hawkins *et al.*, 2015; Woodward, 2017). The standard trend may be extended to an expected constant CN using the following equation (Hawkins *et al.*, 2010):

$$CN(P) = CN_\infty + (100 - CN_\infty) \times e^{-kP} \quad (4.5)$$

where

$CN(P)$ = CN derived, as a function of P, using the asymptotic approach (dimensionless),

CN_∞ = near constant CN observed from CN-P plot, and

k = fitting parameter (mm^{-1}).

Hawkins (1993) indicated that the CN_∞ and k values may be fitted using a least-squares procedure. Figure 4.2 contains a graphical representation of the standard catchment behaviour that was observed by D'Asaro *et al.* (2014) on the Ponte Vecchio catchment, in Italy, with $k = 0.05\ mm^{-1}$ and $CN_\infty = 71$.

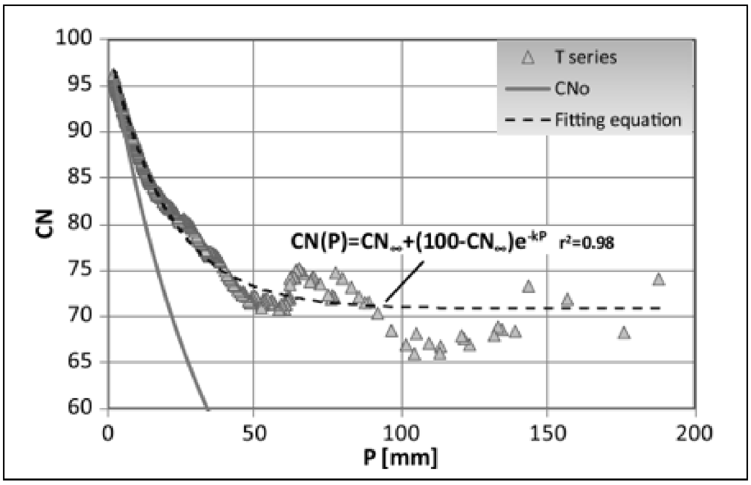

Figure 4.2 The standard catchment behaviour (D’Asaro *et al.*, 2014)

4.4.2 Complacent catchment behaviour

The complacent catchment behaviour is characterized by a decrease in CNs as the rainfall depth increases, however, the CN never reaches a constant value as depicted by the CN-P data series in Figure 4.3. There is no apparent asymptotic value for a complacent catchment, therefore, the runoff may be more aptly calculated using Equation (4.6 (Hawkins, 1993):

$$Q = CP \qquad (4.6)$$

where

C = dimensionless coefficient for the complacent catchment behaviour, $0.005<C<0.05$. The empirical coefficient, C, should be approximated using the percentage imperviousness in a catchment, however, C is usually estimated using P-Q measurements (Hawkins, 1993).

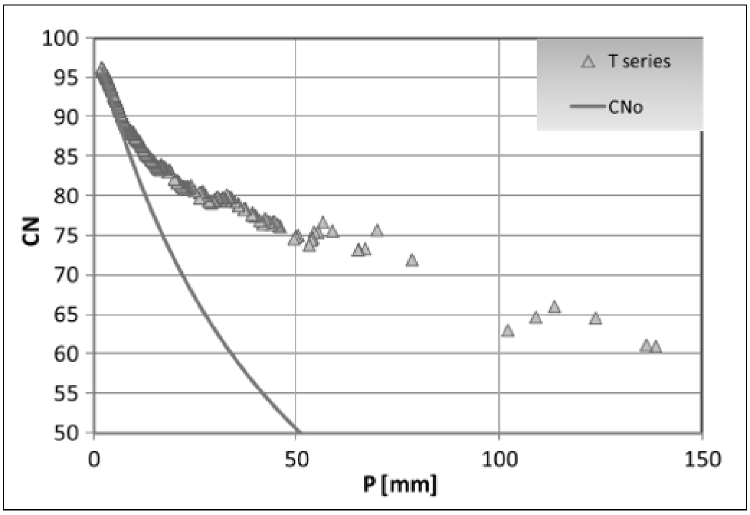

Figure 4.3 Complacent catchment behaviour observed on the Monzanaro catchment in Italy by (D’Asaro et al., 2014)

4.4.3 Violent catchment behaviour

The violent catchment behaviour is characterized by a decline in CN values at higher rainfall depths, as is the case for the complacent behaviour. However, there is an abrupt rise in the CN, and hence runoff, after a Threshold-Rainfall (P_s) value. The P_s generally ranges from 25 to 75 mm (D’Asaro *et al.*, 2014). Figure 4.4 contains an illustration of the violent catchment behaviour with a CN_∞ and kv value of 79 and 1.057 mm^{-1} respectively. For catchments that display the violent behaviour pattern, the following equation had been derived to extend the violent trendline to a more asymptotically constant CN (Hawkins *et al.*, 2009; Hawkins *et al.*, 2010):

$$CN(P) = CN_\infty \times \left(1 - e^{-kv(P - P_s)}\right), \text{ when } P>P_s \qquad (4.7)$$

where

P_s = threshold rainfall depth (mm), and

kv = fitting parameter, different from k, (dimensionless).

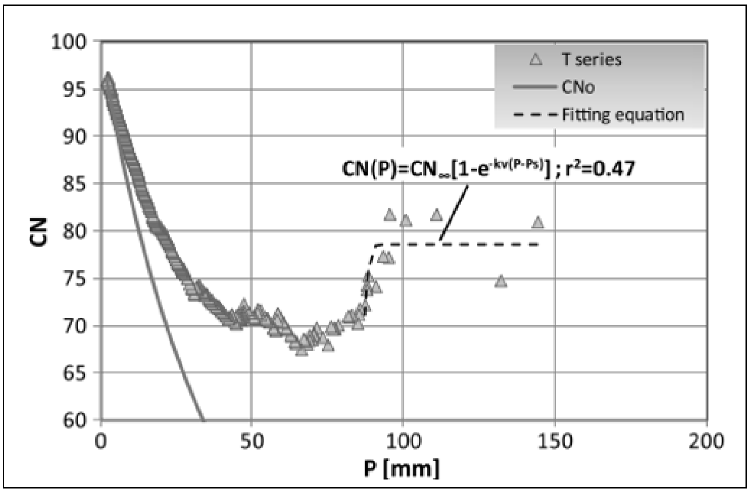

Figure 4.4 The violent catchment behaviour observed on the Pozzillo catchment in Italy by (D’Asaro et al., 2014)

In the standard and violent cases, the equilibrium, or near constant, CN that is observed at high rainfall depths are fitting with respect to higher rainfall design situations (Hawkins *et al.*, 2009). In these two cases, the mean value of all the near constant CNs may be taken as the representative CN of the catchment (Hawkins *et al.*, 2009). The asymptotic determination of CNs was tested using available catchment data from 37 catchments in the USA, India, Pakistan, New Zealand and Africa (Hawkins, 1993). Hawkins (1993) found that the standard, violent and complacent catchment behaviour patterns were observed on 70 %, 10 % and 16 %, of the catchments respectively. Soulis and Valiantzas (2012) and Kowalik and Walega (2015) used the asymptotic approach to derive CNs and both studies revealed that the ‘asymptotic CN’ and rainfall depth are strongly related. Numerous other researchers concluded that the asymptotic approach is a viable method to derive CNs (Tedela *et al.*, 2011; D’Asaro *et al.*, 2014; Woodward, 2017).

CN maps may be used to graphically represent the different CNs that occur on a catchment (Hawkins *et al.*, 2009). Section 4.5 of this document focuses on the generation of CN maps using Geographic Information Systems (GIS).

4.5 The Generation of CN Maps using GIS

The conventional CN derivation methods are time-consuming, error-prone and require significant effort on inaccessible terrain (Deshmukh *et al.*, 2013; Meshram *et al.*, 2017). Numerous studies have indicated that a satisfactory level of accuracy in runoff generation may be obtained when remotely sensed estimates of LULC, soil maps and authoritative CN tables are used with GIS to map CNs (Jackson and Rawls, 1981; Schulze and Schmidt, 1987; Shadeed and Almasri, 2010; Bansode and Patil, 2014). According to Mishra *et al.* (2007), GIS technology could be used to overlay and combine different data into a single computerized map, which summarizes geographic and scientific land attributes. Since all the factors of the SCS-CN model are geographic in nature, the use of Remote Sensing (RS) and GIS techniques to map CNs are becoming increasingly popular (Meshram et al., 2017). Hawkins et al. (2009) indicated that the following steps should be used to generate CN maps:

(a) RS should be used to source landcover data.
(b) GIS are used to superimpose landcover and HSG maps.
(c) The landcover and HSG combinations are then used to obtain CNs from an accepted CN table.
(d) These CN values are then assigned to specific areas, on a map, using GIS.

A study was carried out by Khaddor and Alaoui (2014) to develop methods to map CN values, for a river basin in Northern Morocco, using GIS techniques. The effectiveness and feasibility of the method were tested by simulating runoff for an 80 mm precipitation event. The results indicated that when the SCS-CN method was used in conjunction with RS and GIS, runoff may be conveniently and effectively estimated (Khaddor and Alaoui, 2014). This method was also successfully used to assign the CN to a small agricultural catchment in Poland (Banasik and Woodward, 2010).

4.5.1 Sources of South African land cover data

There has been a frequent call for accurate and updated land cover information in SA (Tshikovhi, 2015). A major source of land cover information is earth observations using satellite imagery. The recent global accessibility of Landsat 8 imagery led to the production of a National Land Cover (NLC) map, NLC 2013, for the years 2013-2014 (GTI, 2015; Ngcofe and Thompson, 2015). The landcover dataset had been created by *GEOTERRAIMAGE* (*GTI*) and is accessible as a commercial data product (GTI, 2015). Spatial datasets of the 2013/2014 NLC have been made available, to the public, by the South African National Biodiversity Institute (Terrapon, 2009; Tshikovhi, 2015). In addition, an updated NLC for 2017/2018 will soon be available (Clark, 2019).

4.5.2 Sources of South African soil data

Information about HSGs are critical when using the SCS hydrograph generating technique (Schulze, 2019). Therefore, a detailed map, at the spatial resolution of South Africa’s 27 491 Terrain Units (TU), of the SCS runoff related HSGs has been produced (Schulze, 2019). The new map, with a higher spatial resolution, also contains the entire spectrum, of SCS-SA HSGs, from low runoff producing (A soils) to the high runoff producing (C/D and D) soils. The map of SCS-SA soil groups is at a spatial resolution that was not previously attempted across SA and may, therefore, be seen as an important new tool for the country’s hydrologists and design engineers (Schulze, 2019). The mapping of SCS soil groups across SA at the resolution of TUs was successfully completed and the maps, that are compatible with a GIS, are available for use (Schulze, 2019).

The importance of the relationship between AMC, CNs and runoff has been previously mentioned in this document. The next Chapter focuses on the methods that are used to account for AMC when using the SCS-CN method.

5. ACCOUNTING FOR AMC WITHIN THE SCS-CN MODEL

The AMC, of a catchment, may be defined as the soil moisture condition preceding a runoff-producing rainfall event (Mishra *et al.*, 2007). Therefore, for accurate runoff estimation, the AMC of a catchment must be accounted for.

5.1 Methods to Account for AMC on a Catchment

There are various methods available to adjust the runoff response, of a catchment, based on the catchment Soil Moisture Status (SMS). These methods, which are mainly concerned with accounting for the change in a catchment's SMS over time, range from simple empirical methods to complex SM budgets (Ghile, 2004).

5.1.1 The original SCS procedure of CN adjustment for AMC

Ghile (2004) reported that examination of the CN_{II} values published by the SCS (NEH, 1959; cited by Schulze and Schmidt, 1987a), indicated that the same CN_{II} values could occur for different land cover/treatment classes and HSGs (Schulze *et al.*, 1992). Theoretically, if the CN_{II} and P values remain constant, the simulated runoff, calculated using Equation (3.4, would be the same. However, in reality, the same rainfall event would generate different runoff volumes, in different areas, because each area would have a different AMC (Ghile, 2004). Schulze and Arnold (1979) and Schulze and Schmidt (1987) both reported that in the SCS-CN procedure of CN adjustment for AMC, the AMC was estimated using the sum of the rainfall occurring five days before the rainfall event being considered. Table 5.1 contains a description of the three antecedent moisture classes in terms of their stormflow potential.

Table 5.1 Description of the antecedent moisture classes (Schulze and Arnold, 1979)

AMC Class	Description
AMC_I	The stormflow potential from this class is low, and catchments in this class are characterised by dry antecedent conditions.
AMC_{II}	This class is termed the average class where average AMC conditions prevail.
AMC_{III}	The stormflow potential from this class is the highest, and catchments in this class are characterised by wet conditions.

A review of the popular formulae used to adjust the CN for AMC (using the original AMC classes) was done, by Mishra *et al.* (2007) and Schulze and Schmidt (1987). Table 5.1 contains a summary of the common formulae that are used to adjust the CN for AMC.

Table 5.2 Popular formulae that are used to adjust the CN based on AMC (after Mishra et al., 2007)

Method	AMC_I	AMC_{III}
Sobhani (1975; cited by Mishra et al., 2007b)	$CN_I = \frac{CN_{II}}{2.334-0.01334CN_{II}}$	$CN_{III} = \frac{CN_{II}}{0.4036+0.005964CN_{II}}$
Hawkins et al. (1985)	$CN_I = \frac{CN_{II}}{2.281-0.01281CN_{II}}$	$CN_{III} = \frac{CN_{II}}{0.427+0.00573CN_{II}}$
Chow et al. (1988)	$CN_I = \frac{4.2CN_{II}}{10-0.058CN_{II}}$	$CN_{III} = \frac{23CN_{II}}{10+0.134CN_{II}}$

The catchments CN_{II} values were established, using soil and LULC characteristics, for the AMC_{II} condition and should, therefore, be adjusted for the AMC prior to a storm using the chosen CN-conversion formulae. The adjusted CN (CN_I or CN_{III}) may then be substituted into Equation (3.5 to compute S, which is then used to compute the runoff (Schulze and Arnold, 1979). When this method was used to determine the catchment SMS, some scale and conceptual limitations arose (Hawkins, 1978). A major limitation was that Evapotranspiration (ET) was only considered in gross terms (dormant or growing season) when assigning the antecedent moisture class. Secondly, the relationship between CNs and the catchment SMS were shown to be discrete and not continuous (Schulze and Schmidt, 1987). Therefore, abrupt or sudden changes in the CN values resulted in possible “quantum jumps” in the calculated runoff (Hawkins, 1978).

5.1.2 Hawkins procedure of CN adjustment for AMC

Based on the limitations, of the original SCS-CN adjustment procedure, that were highlighted in Section 5.1.1, Hawkins (1978) developed an alternate method to adjust the CN to account for AMC. The new method took ET, Q, P and Drainage (D) into account and expressed the relationship between the catchment SMS and CNs as a continuum. The method was based on the following principle (Schulze and Schmidt, 1987):

$$V_2 = V_1 + ET + D - P + Q \tag{5.1}$$

where

V_2 = storage available at time = 2 (mm),

V_1 = storage available at time = 1 (mm),

ET = evapotranspiration losses (mm),

D = interim drainage (mm),

P = interim rainfall depth (mm), and

Q = interim stormflow depth (mm).

This principle was then used to compute a final CN (CN_f), based on the change in SM (V_2-V_1 = ΔS) (Schulze and Schmidt, 1987):

$$CN_f = \frac{(1 + c) \times 1000}{\frac{(1 + c) \times 1000}{CN_{II}} - \frac{(\Delta S)}{25.4}} \qquad (5.2)$$

where

CN_f = adjusted CN, calculated using the catchment SMS (dimensionless), and

ΔS = index of change in catchment SM storage (mm).

The Hawkins approach to adjust the CN for the catchment SMS gave significantly improved estimates of runoff volumes, on experimental catchments, when compared to the original SCS-CN adjustment procedure (Schulze and Arnold, 1979). However, for design analysis, a regional index of SM storage change (P - Q - D – ET) was required for events of design magnitude (Schulze and Schmidt, 1987). The next two sections outline the determination of such indices for 712 homogeneous climatic zones in southern Africa. The SM budgeting procedure, used by the SCS-SA model to account for the catchment SMS, had been verified on 20 catchments in the USA (Schulze, 1984), and are frequently applied in design practice in southern Africa (Ghile, 2004).

5.1.3 MCM of CN adjustment for AMC

Schulze and Schmidt (1987) developed a regionalised MCM to account for AMC in southern Africa. The MCM may be used to adjust the CN_{II} values, to a CN_f using Equation (5.2. Due to limited computing power when the MCM was developed, only the five highest daily rainfall events were selected for each year. For the selected events, accumulated 5- and 30-day rainfall totals were stored. Thereafter, a frequency analysis of the 5- and 30-day rainfall totals were undertaken. For each of the 27 land use/soil categories, moisture budgets were computed for each event selected for a 30-day antecedent period and the 30-day antecedent ΔS was stored (Schulze and Schmidt, 1987). A frequency analysis was undertaken for the 30-day ΔS totals of each land use/soil category and the median (50th percentile) condition ΔS was then computed from the long-term (≈ 30 years) daily rainfall record. This ΔS value, that was expected to occur most frequently statistically, was substituted into Equation (5.2 to compute the CN_f. A major limitation of the MCM is that the T-year RP rainfall event is assumed to result in the T-year RP flood (Schulze and Schmidt, 1987). Dunsmore *et al.* (1986) concluded that there was little association between rankings of daily rainfall and the resulting runoff depths and the assumption that the T-year rainfall produces the T-year runoff does not provide a sound basis for hydrological design (Dunsmore *et al.*, 1986; Schulze and Schmidt, 1987).

5.1.4 The joint association of rainfall, runoff and antecedent soil moisture conditions

Measures to account for the joint association between rainfall, runoff and AMC, in the SCS-SA model, were applied in combination with Equation (5.2 and the *ACRU* SM budgeting model (Schulze and Schmidt, 1987). When using the JAM to account for the catchment AMC, the *ACRU* model was used to simulate the antecedent actual ET, D and Q, for 27 land use and soil combinations using a 30-day antecedent period, to compute the ΔS prior to a specific event. This ΔS value was substituted into Equation (5.2 to compute the CN_f. Thereafter, daily stormflow depths were computed for each event and a frequency analysis of the AM stormflow depths provided approximations of design stormflow depths (Schulze and Schmidt, 1987). The joint association approach carried out a frequency analysis on the simulated stormflow depths, of the five largest events recorded in each year. Therefore, the JAM accounts for conditions when the largest flood is produced by an event (such as the 2nd, 3rd or 4th largest rainfall event) which is not the largest rainfall event for the record period (Schulze and Schmidt, 1987; Schulze *et al.*, 2004; Rowe, 2015). The use of *ACRU* to account for the variation of the AMC between storms, occurring on a catchment, implied that rainfall of a given RP does not automatically produce stormflow of an equal RP and a smaller rainfall producing event occurring on a wet catchment may result in a larger flood event than a larger rainfall event occurring on a dry catchment (Schulze and Schmidt, 1987). Internationally, the event-based SCS-CN method has also been modified and used in conjunction with CS models with inter-dependent runoff and SM accounting components. The next two sections describe how AMC are accounted for when applying the SCS-CN method with a CS model.

5.2 Soil Moisture Accounting Procedure

Michel *et al.* (2005) developed a new version of the SCS-CN formula. The new formula was reported as being more consistent from a Soil Moisture Accounting (SMA) perspective. According to Michel *et al.* (2005), if the SCS-CN method was to be applied within a CS model, the method should not be restricted to the total runoff depth. It is important for the SCS-CN model to be accurate at any instant throughout the duration of the storm. The original SMA procedure, in the SCS-CN model, was based on the concept that a larger moisture store level, resulted in a larger fraction of rainfall being transformed into runoff. This notion implied that if the SM store was full, all rainfall would be converted into runoff. Based on this idea, it was proposed by Michel *et al.* (2005) that the SM store level at the commencement of a rainfall event (V_o) should be included in Equation(3.4. It is the opinion of Michel *et al.* (2005), that the S value should not be related to the catchment AMC, because S is an inherent parameter of the model. Therefore, S was taken to be the sum of Ia and V_o, and this new intrinsic parameter was termed S_a. Table 5.3 contains the new stormflow equations, with a continuous SMA process, that was proposed by (Michel *et al.*, 2005).

Table 5.3 Stormflow equations that were derived using a continuous SMA procedure (Michel et al., 2005)

Equation	Conditions
$Q = \frac{(P + V_o - S_a)^2}{P + V_o - S_a + S}$	$S_a - P < V_o < S_a$
$Q = 0$	$V_o \leq S_a - P$
$Q = P(1 - \frac{(S + S_a - V_o)^2}{S^2 + (S + S_a - V_o)P})$	$S_a \leq V_o \leq S_a + S$

These equations were tested on 140 French catchments, by Michel *et al.* (2005), and the average water content of the SMA reservoir, from the catchments, were used to select the V_o values. On average, the study indicated that the V_o to S ratio had a median value of 0.61, a lower decile of 0.33 and a higher decile of 0.87. On this basis, Michel *et al.* (2005) simplified the equations presented in Table 5.3, by equating S_a to 0.3S, and the AMC were taken into account by replacing V_o with a fraction of S. Table 5.4 contains the equations that were developed, using a continuous SMA procedure, to account for AMC (Michel *et al.*, 2005).

Table 5.4 Stormflow equations that account for AMC

AMC Condition	Equation
AMC_I ($V_o = 0.61S$)	$Q = \frac{P(P)}{S + P}$
AMC_{II} ($V_o = 0.33S$)	$Q = \frac{P(0.48S + 0.72P)}{S + 0.72P}$
AMC_{III} ($V_o = 0.87S$)	$Q = \frac{P(0.79S + 0.46P)}{S + 0.46P}$

The improved SMA procedure was developed, by Michel *et al.* (2005), to address structural inconsistencies, such as S being considered an intrinsic parameter that was dependent on catchment AMC, in the original SCS-CN method. Kannan *et al.* (2008) stated that a proper continuous SMA procedure was required by models using the CN method. Kannan *et al.* (2008) proposed that a simple, single-parameter model, based on the SCS-CN methodology, should be developed to be used in CS models. For the retention parameter to be used in CS modelling, the S value was associated with a robust continuous SMA procedure to avoid unexpected jumps in the CN, from one moisture condition to another. The following instantaneous retention parameter equation was derived by Kannan *et al.* (2008):

$$S_t = S_{max} + ET_t \times e^{-B} - P + Q \qquad (5.3)$$

where

S_t = SM retention parameter at time t,

S_{max} = maximum value of the retention parameter,

ET_t = potential ET at time t,

B = moisture depletion coefficient,

P = rainfall depth at time t, and

Q = runoff depth at time t.

The depletion coefficient (B), is the only parameter that is linked to the SMA procedure. Theoretically, B ranges from 0 to 2, however, the practical limits of B are from 0.5 to 1.5 and the model was calibrated by varying B until the observed and simulated runoff values were similar (Kannan *et al.*, 2008). The sensitivity and behaviour of the single parameter model and the depletion coefficient were tested on four catchments in the USA and the model performed reasonably well when calculating runoff, and the parameter calibration was easy (Kannan *et al.*, 2008).

5.3 Revised Soil Moisture Index

Between 1950 to 1980, Equation (3.4 was used by the NRCS in a continuous mode to evaluate numerous hydraulic structures that were designed (Kannan *et al.*, 2012). The revised Soil Moisture Index (SMI) is associated with the CN approach (Jajarmizadeh *et al.*, 2014). However, the CN approach was enhanced by substituting the five-day antecedent rainfall with a SMI that was computed using a daily water-yield model (Kannan *et al.*, 2012). The SMI may be determined using rainfall, runoff, and ET, and is, therefore, only suitable on catchments where observed data are available (Jajarmizadeh *et al.*, 2014). Since the CN is computed as a function of plant ET, the CN value becomes less reliant on soil storage and more dependent on the antecedent climate conditions (Jajarmizadeh *et al.*, 2014). In the revised SMI method, the S value, that is updated at the end of every day, is computed using the following equation (Kannan *et al.*, 2012; Jajarmizadeh *et al.*, 2014):

$$S_t = S_t - 1 + ET \times \exp\left(\frac{-BS_t - 1}{S_{max}}\right) - P + Q \tag{5.4}$$

where

S_t = retention parameter at the present time step (mm),

S_{t-1} = retention parameter at the previous time step (mm),

B = depletion coefficient (dimensionless),

S_{max} = maximum value of the retention parameter (mm).

The revised SMI approach was used together with the SCS-CN method in numerous runoff simulation models (Kannan *et al.*, 2012) and the results indicated that the revised SMI method produced accurate runoff estimates over a broad range of soil properties (Jajarmizadeh *et al.*, 2014).

5.4 Adjusting the CN, for AMC, using Climatic Zonation

A study by Ghile (2004) hypothesised that in similar climatic regions the median ΔS values, from the initial catchment conditions, were likely to be similar, and in different climatic regions the median ΔS values were likely to vary. Consequently, it was suggested that climatic regions should be characterized using a standard climate classification system called the Koppen Climate Classification (KCC). Therefore, the SMS of a catchment was treated as a climatologically influenced variable. Zones occurring within each individual KCC class displayed homogeneity of median ΔS values that were derived using the *ACRU* SM budgeting model. When the *ACRU*-Koppen method was used to adjust the CN_{II}, for AMC, the ΔS value was estimated using the Mean Annual Precipitation (MAP) for a given KCC and soil and land use combination. The SCS-SA and *ACRU*-Koppen method for stormflow modelling were tested on the same catchment. The results indicated that the *ACRU*-Koppen method displayed better levels of performance than the SCS-SA model. The good simulations of ΔS, that were similar for each KCC, indicated that the KCC may be used as a surrogate method to adjust the CN_{II} values, for AMC, when there is limited availability of hydrological and monthly climatological information.

6. DISCUSSION AND CONCLUSIONS

An increasing number of intense, unpredicted rainfall, and hence, flood events have been documented in the recent past. An under-estimation of design floods may result in a loss of resources and lives and the over-design of a structure has severe economic consequences. There is, therefore, a great need for accurate DFE in SA. The SCS-CN model is a popular method that is used for DFE globally, and in this method, the calculated runoff depth is most sensitive to the rainfall depth, CN and AMC.

The original CN_{II} values were derived using the rainfall-runoff depths for the maximum flood peaks that were observed each year and the CN_{II} values were obtained based on interpretations of P-Q data that were plotted on arithmetic paper. For soil and landcover classes where no observed data was available, the CNs were obtained via interpolation. These CNs have been used authoritatively, however, the method used to derive the CNs are subjective and depends largely on the spread of P-Q data for a specific soil-landcover complex. There is, therefore, a need to derive new CNs for unlisted land cover classes. A possible improvement on the use of CNs from the handbook tables is to use local data and frequency matched P-Q pairs to determine CNs. Numerous researchers have highlighted that CNs vary with rainfall depth. Therefore, using a single or few rainfall events to calculate an average or median CN is not feasible. Hence, the asymptotic approach, that uses all the rainfall values, could provide reasonable CN estimates. The asymptotic approach to derive catchment CNs has the advantage of being mathematical and it appears to give results which are consistent with the original CN derivation procedure. The asymptotic approach has been extensively tested and is simple to apply, however, selecting an 'asymptotic CN’ may be subjective and dependent on the individual that is interpreting the CN-P plots. The conventional methods of CN derivation are error-prone and time-consuming. In SA, up-to-date HSG and land cover maps are available at a national scale. These maps and CN tables could be successfully integrated into a national CN map using GIS techniques. However, for this method to be successful, the land cover and HSG data, for all catchments, must be available in a format that is compatible with the GIS that is used and the CN maps will only be as accurate as the CNs that are used to generate the maps.

Numerous studies have indicated that the catchment SMS, prior to runoff producing rainfall events, play a vital role in determining the magnitude of the resulting runoff. Therefore, the AMC of a catchment needs to be considered for accurate runoff estimation when using the SCS-CN method. In the original SCS-CN method, the CN was adjusted, for AMC, using the

5-day accumulated rainfall for wet and dry catchment conditions. This method was not effective because the CN was treated as a discrete variable, therefore, sudden changes in the CN resulted in jumps in the simulated runoff. Based on these limitations, a procedure was developed to treat the relationship between AMC and the CN as a continuum. This procedure was used to compute a change in SM which was then used to compute a CN_f that accounted for the AMC of a catchment. A major strength of the SCS-SA model was the development of methods to consider typical AMC using the MCM and to estimate runoff by the joint association of rainfall, runoff and AMC when using the JAM. Both the MCM and JAM have limitations that could possibly be overcome if the results from a CS model, and the longer rainfall records that are now available, are used to update the MCM and JAM. When the SCS-CN model is used together with a CS model, the SMA and revised SMI procedure may be used to account for AMC on a catchment. When a SMA procedure is used, the S value is treated as an intrinsic parameter. However, the runoff is only computed for dry, wet and average catchment conditions, therefore, there could still be jumps in the computed runoff value when using this method. A simple, single retention parameter model based on the SCS-CN model was developed to be used in CS models. An advantage of this method would be that unexpected jumps in CN, from one moisture condition to another, are avoided. The continuous CN approach was further enhanced by using the revised SMI approach, where the 5-day antecedent rainfall was replaced with a SMI. The revised SMI method produced accurate runoff estimates over a broad range of soil properties and may, therefore, be a viable method to account for AMC on a catchment. A standard climate classification, such as the KCC, could be used to characterise similar climatic regions. The standard climate classification may be used as a surrogate method to adjust the runoff CNs, for AMC in areas with inadequate sources of hydrological and climatological data. This method is significant because the runoff is calculated as a function of the climate of the catchment.

The SCS-SA model, that was developed in the late 1970s and 1980s, clearly needs to be updated and refined. The updated model should incorporate the increased spatial resolution of information, that is presently available, and the updated and improved design rainfall values, while simultaneously improving the techniques used to account for AMC. A CS model should be used to update and refine the procedures, used in the SCS-SA model, to account for AMC. The original tabulated CNs were derived from AM event values and may, thus, result in inaccurate runoff estimates. Therefore, new CNs need to be calculated using local P-Q data, the asymptotic CN derivation approach or GIS techniques that use updated land cover and soils data to generate CN maps.

7. PROJECT PROPOSAL

From the above literature review, it is evident that the SCS-SA model requires to be updated and refined. This chapter contains a proposal for the further development, updating, and assessment of the SCS-SA model for DFE, in SA, using a CS approach.

7.1 Problem Definition

The SCS-SA method is a versatile and popular method that is widely used to calculate the runoff volume and peak discharge from a rainfall event. Schulze and Arnold (1979) and Schulze and Schmidt (1987) adapted the SCS-CN approach to southern African conditions, and the new SCS-SA model accounted for: (a) regional differences in AMC prior to significant rainfall events, and (b) the joint association between rainfall, runoff and AMC (Schulze and Schmidt, 1987; Smithers and Schulze, 2002). However, Smithers and Schulze (2002) pointed out that enhanced computing power and currently available databases would allow for the refinement of the SCS-SA model. The updated SCS-SA model should take the increased spatial resolution of information, that is presently available, and the improved design rainfall values into account. It was also suggested that the techniques used to account for AMC should be improved (Smithers and Schulze, 2002). One of the main weaknesses of the SCS-CN method, that was reported by Soulis and Valiantzas (2012), was that the method did not explicitly consider the effect of AMC. CS modeling could be used to re-evaluate and improve the MCM of accounting for AMC on a catchment (Smithers and Schulze, 2002). Currently, the JAM can only be used for RPs less than or equal to 20 years. This could be improved if a CS approach is used because longer rainfall records are currently available, therefore, design events with a RP greater than 20 years may be used to improve the JAM (Smithers and Schulze, 2002). According to Hawkins (2014), the CN concept was established in the “quiet past” and it is, therefore, inadequate for the “stormy present” of hydrologic engineering. The CN tables are based on soils and land cover information that are often far from reality (Hawkins, 2014). With the uncertainty surrounding the origin and development of the CN values, and the sensitivity of the simulated hydrological responses to the CNs used, it is vital to use a CN that best represents the land cover, soil type and hydrologic condition of the catchment of interest. Given the availability of spatially explicit information on land cover and soil types in SA, the derivation of new CNs, using observed or simulated rainfall-runoff data, is required.

7.2 Aim and Objectives

The aim of this study is to:

Further develop, update and assess the SCS-SA model for DFE in SA using a CS approach.

The specific objectives of this study are to:

(a) briefly review two rainfall-runoff methods that are used to estimate runoff,
(b) highlight methods, that are used in SA and internationally, to derive CNs and account for antecedent catchment moisture conditions, and
(c) propose a methodology to verify the existing CN derivation techniques and derive new CNs, if required, based on South African land cover and soil type classifications, update the SCS-SA SM adjustment procedures using the results from the CS model under development (Rowe, 2019) and develop a refined and updated version of the SCS-SA model using the results and methodology from the CS model that is currently under development (Rowe, 2019).

7.3 Research Questions

Research, calculations and data analysis will be done to answer the following questions:

(a) What are the most effective CN derivation techniques that may be used to derive CNs specific to South African landcover and soil classes?
(b) How can the SCS-SA soil moisture accounting procedure be improved using the results from a continuous simulation model?

7.4 Proposed Methodology

The proposed methodology to achieve the aims and objectives of the study include a thorough review of literature based on the use of the CN method in SA and internationally. Initially, an in-depth literature review focussing on CN derivation techniques and methods to account for AMC, when using the CN method, will be done. This will provide an understanding of methods that are currently used locally and internationally. The applicable methods will be identified, tested and adapted to South African conditions if required. The CN derivation techniques that are highlighted in Chapter 4 will be tested and potential improvements to the MCM and JAM will also be investigated and applied, if necessary. The degree to which the proposed aims and objectives will be met depends on the amount of reliable rainfall-runoff data that are available.

The updated SCS-SA model will be used to simulate runoff, using rainfall data, on catchments in SA. The following sections will provide an overview of the proposed methodology to achieve the above-mentioned aims and objectives.

7.4.1 CN derivation using South African landcover classes

The CN derivation techniques, mentioned in Chapter 4, will first be applied using observed data, thereafter, simulated data will be used to derive CNs if required. If simulated data is used, the new CNs could be derived, for South African land cover and soil type classifications, using the results simulated by the *ACRU* model. The CS results from *ACRU* will be verified against the observed Q and P data. The CNs could also be derived graphically using the asymptotic approach or using the equations discussed in Sections 4.1 and 4.2 of the literature review. These CN derivation techniques will be used to derive CNs for existing landcover and HSGs. The derived CNs will be compared to the current CNs that are used by the SCS-SA model. This will serve as a verification of the accuracy of the specific CN derivation technique. The most accurate CN derivation technique will be used to derived CNs for South African landcover and soil classes. If the CN derivation process is data intensive, a MATLAB script will be written to calculate the CNs more efficiently. SCS-SA will then be used to calculate runoff for catchments that have observed rainfall-runoff data available. The observed runoff data will then be compared to the simulated runoff data from the updated SCS-SA model and the original SCS-SA model to gain confidence in the new CNs. The SCS-SA design events need to be revised and these design events could be compared to design events from observed data from the catchments that are simulated.

7.4.2 Adjusting the CN for AMC using the results from a CS model

The runoff response from an event-based model could be improved, using the SMS calculated using *ACRU*. The following steps may be taken to account for AMC:

(a) The change in SM could be calculated for various antecedent periods (not only over a 30-day period) prior to the design rainfall event.

(b) ΔS could be simulated using the *ACRU* model at a quaternary or quinary catchment scale for various combinations of vegetation and soil properties. South African landcover and soil types will be used in these simulations.

(c) Numerous, not only 50th percentile, values of ΔS would then be computed from a long-term (≈ 30 years) daily rainfall record

(d) The ΔS values from the above step, would then be used with Equation (5.2 to compute the CN_f.
(e) Investigations will be done to determine if AMC can be linked to RPs to improve the model simulations.

The following steps may be used to update the JAM:

(a) The *ACRU* model may be used to simulate the antecedent actual ET, D and stormflow for, selected South African land cover and soil combinations using various, not only the 30-day, antecedent period, to compute the change in SM conditions (ΔS).
(b) The above ΔS value will then be substituted into Equation (5.2 to compute the CN_f.
(c) After adjusting the CN_{II} for the dominant AMC, daily stormflow depths will be computed for each event.
(d) Thereafter a frequency analysis of the simulated discharges of the five largest events in every year of record (P-Q data for more than 20 years are now available) will be done.

7.4.3 Assessment of the refined and updated SCS-SA model

The CS model, that was developed, for SA, by Rowe (2019), will be configured at quaternary or quinary spatial scales for SA, using default assigned climate, soils and land cover information. The driver rainfall stations used in the simulation will be updated (provided the data may be obtained from the South African Weather Service (SAWS) and the Centre for Water Resources Research (CWRR) at the University of KwaZulu-Natal). The simulation results per quaternary or quinary catchment will then be used to refine and update the way that the SCS-SA model accounts for AMC and the joint association of rainfall and runoff, at the selected spatial scale. The Nash-Sutcliffe efficiency coefficient will be used to assess the predictive power of the updated SCS-SA model. For selected catchments, the hydrographs of observed and simulated runoff, from the original and updated SCS-SA model, will be plotted to provide a visual representation of the model performance.

7.5 Resources Required for the Study

The following resources will be required to ensure the successful completion of the project:

(a) Microsoft Office software (UKZN license),
(b) Endnote Referencing software (UKZN license),
(c) GIS software (UKZN license),

(d) hydrological data from SAWS and the CWRR at the University of KwaZulu-Natal,
(e) statistical software (UKZN license), and
(f) access to the Internet and a printer (at UKZN).

7.6 Project Plan

To complete the research project effectively and timeously, it is vital to schedule all activities. The project is expected to take a total of 18 months to complete. A detailed list of short-and-long term goals are presented in Appendix B in the form of a Gantt Chart.

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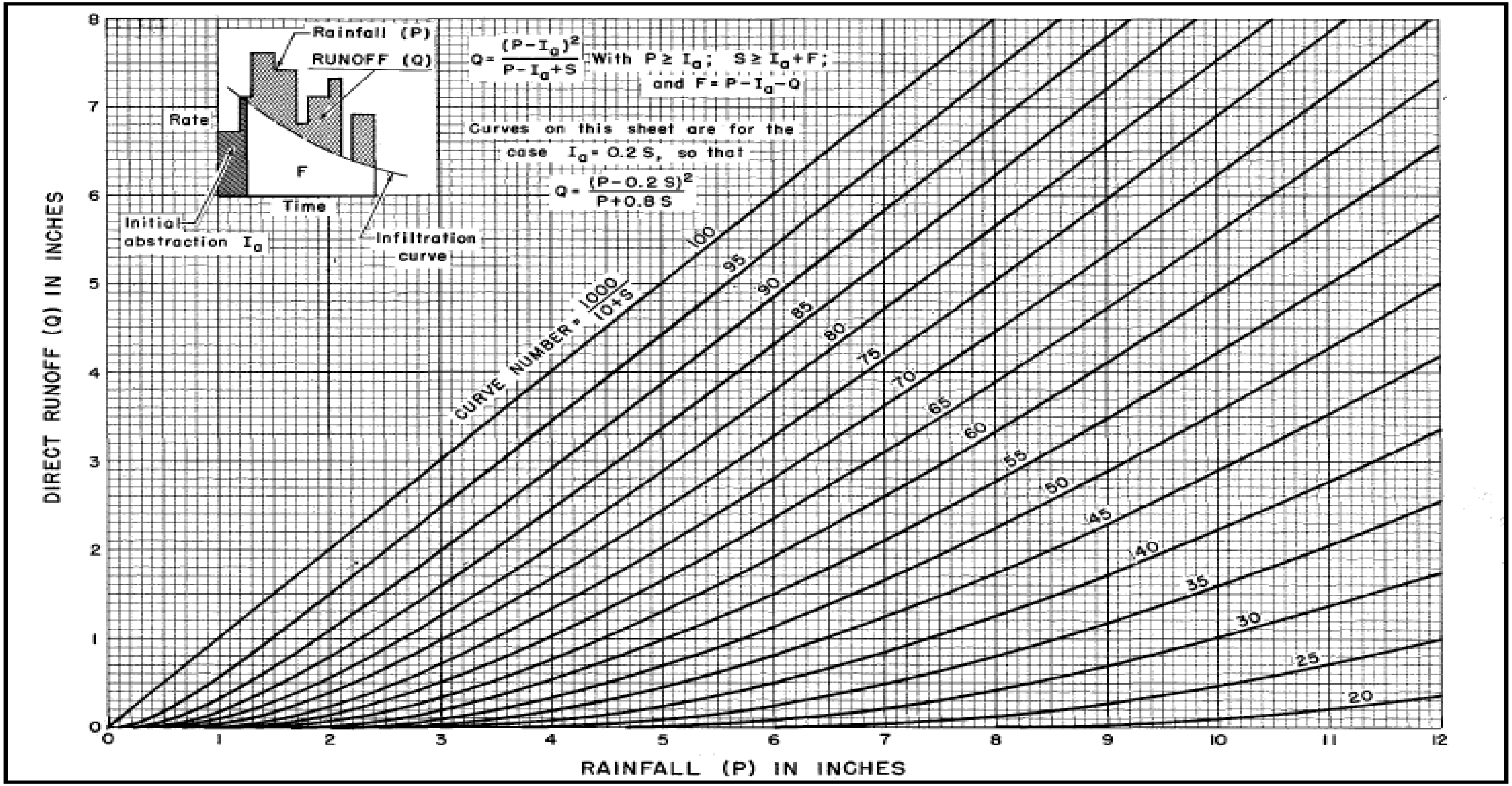
APPENDIX A


Rainfall (P)
RUNOFF (Q)
Rate
F
Time
Initial abstraction I_a
Infiltration curve
$Q = \frac{(P-I_a)^2}{P-I_a+S}$ With $P \geq I_a$; $S \geq I_a+F$;
and $F = P-I_a-Q$
Curves on this sheet are for the case $I_a = 0.2\,S$, so that
$Q = \frac{(P-0.2\,S)^2}{P+0.8\,S}$
CURVE NUMBER = $\frac{1000}{10+S}$
100
95
90
85
80
75
70
65
60
55
50
45
40
35
30
25
20
DIRECT RUNOFF (Q) IN INCHES
0
1
2
3
4
5
6
7
8
RAINFALL (P) IN INCHES
0
1
2
3
4
5
6
7
8
9
10
11
12

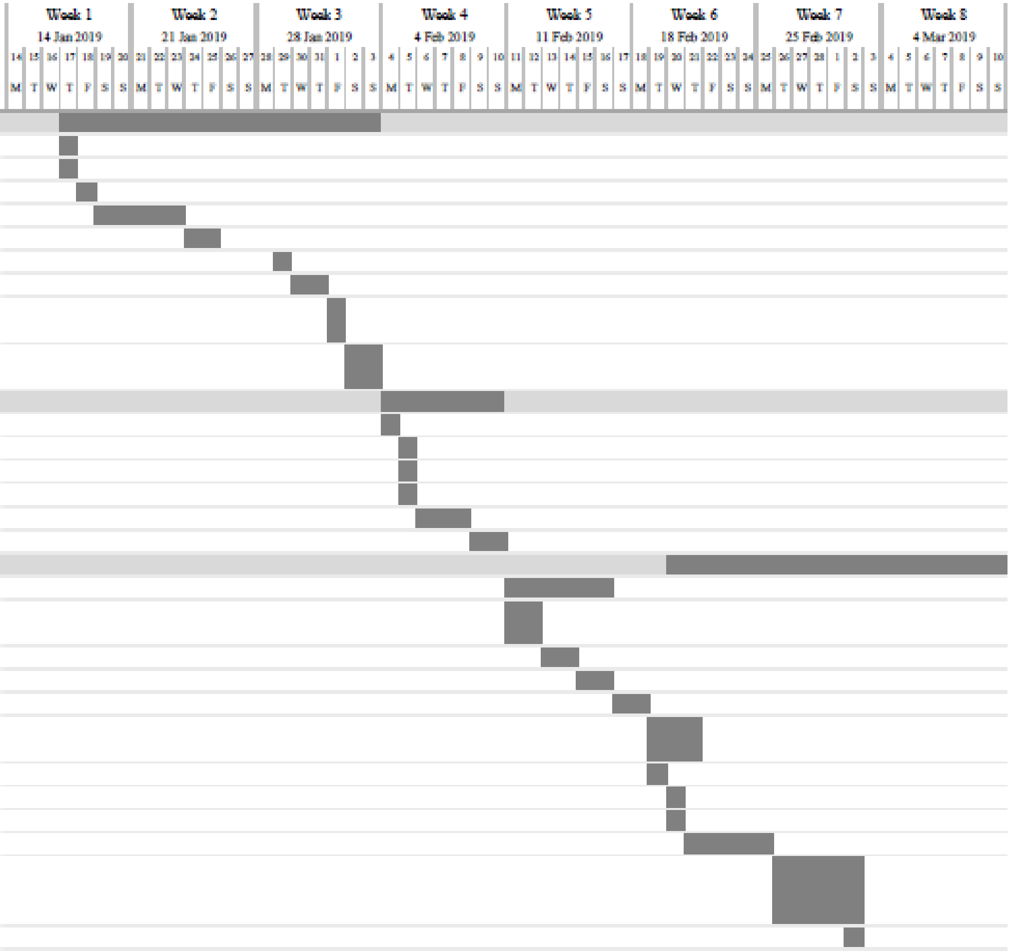
APPENDIX B

Udhav Maharaj MSc-ENG Project Schedule

Udhav Maharaj

Project Start Date 1/17/2019 (Thursday)
Project Supervisor Prof. J.C Smithers
Display Week 1

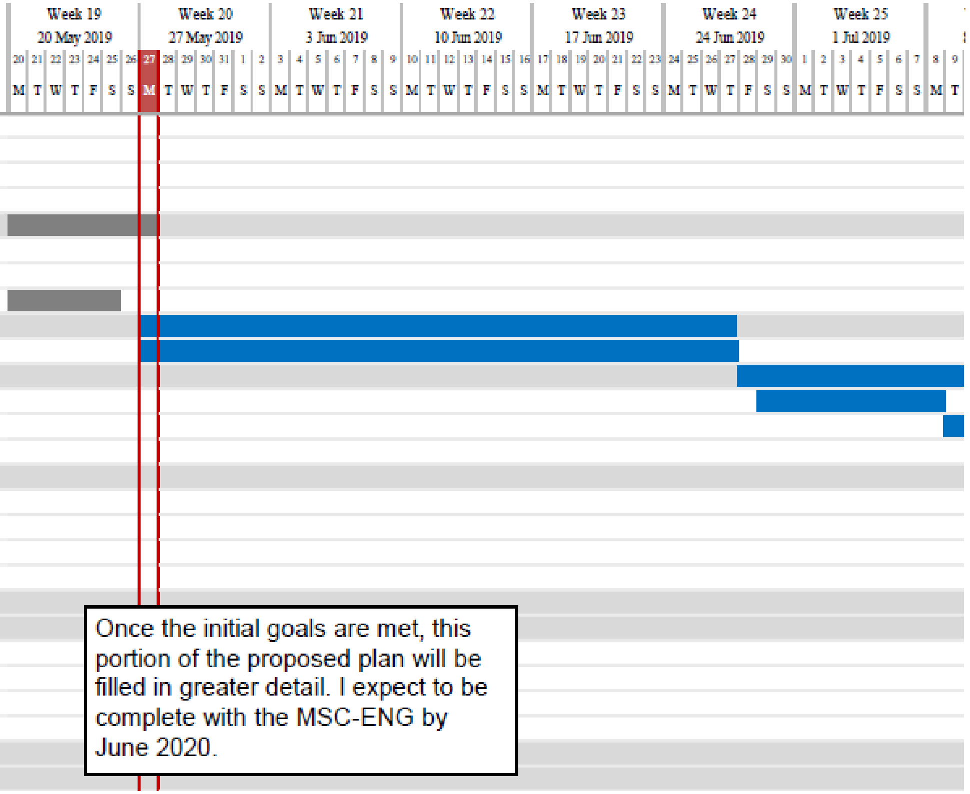
WBS	TASK	LEAD	PREDECESSOR	START	END	DAYS	% DONE	WORK DAYS
1	**Initial Stages of project**			Thu 1/17/19	Sun 2/03/19		100%	12
1.1	Supervisor Selection	Maharaj		Thu 1/17/19	Thu 1/17/19	1	100%	1
1.2	Topic selection	Maharaj and Smithers		Thu 1/17/19	Thu 1/17/19	1	100%	1
1.3	Meeting with Supervisor	Maharaj and Smithers		Fri 1/18/19	Fri 1/18/19	1	100%	1
1.4	Initial Research for topic	Maharaj		Sat 1/19/19	Wed 1/23/19	5	100%	3
1.5	NFSP Workshop			Thu 1/24/19	Fri 1/25/19	2	100%	2
1.6	Meeting with Supervisor	Maharaj and Smithers		Tue 1/29/19	Tue 1/29/19	1	100%	1
1.6.1	Refining Topic	Maharaj and Smithers		Wed 1/30/19	Thu 1/31/19	2	100%	2
1.6.2	Registration Forms Obtained	Maharaj		Fri 2/01/19	Fri 2/01/19	1	100%	1
1.6.3	SANCOLD Scholarship Application	Maharaj		Sat 2/02/19	Sun 2/03/19	2	100%	0
2	**Preliminary planning**			Mon 2/04/19	Sun 2/10/19		100%	5
2.1	Gantt Chart Finalization	Maharaj		Mon 2/04/19	Mon 2/04/19	1	100%	1
2.2	Aims	Maharaj and Smithers		Tue 2/05/19	Tue 2/05/19	1	100%	1
2.3	Methodology	Maharaj and Smithers		Tue 2/05/19	Tue 2/05/19	1	100%	1
2.4	Objectives	Maharaj and Smithers		Tue 2/05/19	Tue 2/05/19	1	100%	1
2.5	Review SCS-SA Knowledge	Maharaj		Wed 2/06/19	Fri 2/08/19	3	100%	3
2.6	Topic Finalised	Maharaj		Sat 2/09/19	Sun 2/10/19	2	100%	0
3	**Draft Literature Review and Project Proposal**			Wed 2/20/19	Mon 4/22/19		100%	44
3.1	Project Proposal	Maharaj		Mon 2/11/19	Sat 2/16/19	6	100%	5
3.1.1	Rationale of Research Project	Maharaj		Mon 2/11/19	Tue 2/12/19	2	100%	2
3.1.2	Research Questions	Maharaj		Wed 2/13/19	Thu 2/14/19	2	100%	2
3.1.3	Research Objectives	Maharaj		Fri 2/15/19	Sat 2/16/19	2	100%	1
3.1.4	Materials and Methods	Maharaj		Sun 2/17/19	Mon 2/18/19	2	100%	1
3.1.5	Work Plan and Time Schedule	Maharaj		Tue 2/19/19	Thu 2/21/19	3	100%	3
3.1.6	Resources List	Maharaj		Tue 2/19/19	Tue 2/19/19	1	100%	1
3.2	Literature Review	Maharaj		Wed 2/20/19	Wed 2/20/19	1	100%	1
3.2.1	Main Title	Maharaj		Wed 2/20/19	Wed 2/20/19	1	100%	1
3.2.2	Introduction	Maharaj		Thu 2/21/19	Mon 2/25/19	5	100%	3
3.2.3	Methodological Approaches to Critical Literature Review	Maharaj		Tue 2/26/19	Sat 3/02/19	5	100%	4
3.2.4	Registration went Through	Maharaj		Sat 3/02/19	Sat 3/02/19	1	100%	0



Project Start Date 1/17/2019 (Thursday)
Project Supervisor Prof. JjC Smithers

Display Week 19

WBS	TASK	LEAD	PREDECESSOR	START	END	DAYS	% DONE	WORK DAYS
3.2.5	Main Literature Review	Maharaj		Sun 3/03/19	Sat 4/06/19	35	100%	25
3.2.6	Discussion	Maharaj		Sun 4/07/19	Sat 4/13/19	7	100%	5
3.2.7	Conclusion	Maharaj		Sun 4/14/19	Fri 4/19/19	6	100%	5
3.2.8	Abstract	Maharaj		Sat 4/20/19	Mon 4/22/19	3	100%	1
4	**Final Literature Review and Project Proposal for Assessn**			Wed 4/24/19	Mon 5/27/19		100%	24
4.1	Edit Draft Document	Maharaj		Wed 4/24/19	Mon 5/06/19	13	100%	9
4.2	Meet with Supervisor	Maharaj		Tue 5/07/19	Tue 5/07/19	1	100%	1
4.2	Prepare and Edit Final Documer	Maharaj		Wed 5/08/19	Sat 5/25/19	18	100%	13
5	**Examination complete**			Mon 5/27/19	Thu 6/27/19		0%	24
5.1	Wait for feedback	Maharaj		Mon 5/27/19	Thu 6/27/19	32	0%	24
6	**Presentation**			Fri 6/28/19	Sat 7/27/19		0%	21
6.1	Prepare Presentation	Maharaj		Sat 6/29/19	Mon 7/08/19	10	0%	6
6.2	Meet with Supervisor	Maharaj and Smithers		Tue 7/09/19	Tue 7/09/19	1	0%	1
6.3	Edit Presentation for Final Prese	Maharaj		Wed 7/10/19	Thu 7/25/19	16	0%	12
7	**Deriving New Curve Numbers for South African Land Cla**			Thu 7/25/19	Fri 11/22/19		0%	120
7.1	Deriving CN using Original SCS	Maharaj		Fri 7/26/19	Sat 8/24/19	30	0%	21
7.2	Deriving CN using Asymptotic A	Maharaj		Sun 8/25/19	Mon 9/23/19	30	0%	21
7.3	Using P-Q Data to Derive CNs	Maharaj		Sun 8/25/19	Mon 9/23/19	30	0%	21
7.4	Generate CN Maps	Maharaj		Tue 9/24/19	Wed 10/23/19	30	0%	22
8	**Comparison Between Original and New Curve Numbers**			Wed 10/23/19	Sat 11/02/19		0%	20
9	**Updating Methods to Adjust for Antecedent Moisture Con**			Sat 11/02/19	Sun 3/01/20		0%	120
7.1	Use SMA Procedure to Account	Maharaj		Sat 11/02/19	Mon 12/02/19	30	0%	30
7.2	Use Revised SMI to Account for	Maharaj		Mon 12/02/19	Wed 1/01/20	30	0%	30
7.3	Update MCM	Maharaj		Wed 1/01/20	Fri 1/31/20	30	0%	30
7.4	Update JAM	Maharaj		Fri 1/31/20	Sun 3/01/20	30	0%	30
8	**Finalising Results and Writing Final Report**			Sun 3/01/20	Thu 4/30/20		0%	20
9	**Proofreading and Submitting Final Document for Examin**			Fri 5/01/20	Mon 6/01/20		0%	22



Once the initial goals are met, this portion of the proposed plan will be filled in greater detail. I expect to be complete with the MSC-ENG by June 2020.