DEVELOPMENT AND ASSESSMENT OF RULES TO PARAMETERISE THE *ACRU* MODEL FOR DESIGN FLOOD ESTIMATION

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ABSTRACT

Design Flood Estimation (DFE) is essential in the planning and design of hydraulic structures. Recent flooding in the country has highlighted the need to review the techniques used to estimate design floods in South Africa, where old and outdated methods are widely applied. In this study the potential of a Continuous Simulation Modelling (CSM) approach to DFE in South Africa is highlighted, identifying the benefits of a CSM approach over event based approaches. The daily time-step *ACRU* agrohydrological model has provided reasonable results for DFE in several pilot studies. A review on hydrological modelling and the links and similarities between the SCS-SA and *ACRU* models, however, highlighted that in terms of land cover information, the land cover classification used in the SCS-SA model accounts for different land management practices and hydrological conditions, which are not accounted for in the current versions of the *ACRU* land cover classification. Since the CNs used in the original SCS model were derived from observations, and the SCS-SA model is an accepted method of DFE in small catchments in South Africa (Schmidt and Schulze, 1987a; Schulze *et al.*, 2004; SANRAL, 2013), it was assumed in this study that the design volumes simulated by the SCS-SA model are reasonable, and that the relative changes in design volumes simulated by the SCS-SA model as a consequence of changes in land management practice or condition are also reasonable. Based on these assumptions, the general approach to the study was to investigate how design volumes simulated by the SCS-SA model for various land management practices or conditions could be simulated by the *ACRU* model, and to derive classes in the *ACRU* hierarchical classification for land management practice and hydrological condition. Consequently, design runoff volumes and changes in design runoff volumes, for different management practices and hydrological conditions, as simulated by the SCS-SA model, were used as a substitute for observed data, *i.e.* as a reference, to achieve similar design runoff volumes and changes in design volumes in the *ACRU* model. This was achieved by adjusting relevant variables in the *ACRU* model to represent the change in management practice or hydrological condition, as represented in the SCS-SA model. After three initial attempts failed to produce comparable simulation results between the SCS-SA and *ACRU* models a sensitivity analysis of *ACRU* variables was conducted in order to identify which *ACRU* variables would represent SCS-SA Curve Numbers (CNs) best for selected land cover classes. The sensitivity analysis identified two *ACRU* variables best suited to achieve this task, namely *QFRESP* and *SMDDEP*. Calibration of *QFRESP* and *SMDDEP* values against

CN values for selected land cover classes was performed. A strong relationship between these *ACRU* variables and CN values for selected land cover classes was achieved and consequently specific rules and equations were developed to represent SCS-SA land cover classes in *ACRU*. Recommendations, however, are suggested to further validate and substantiate the approach and developed rules and equations.

PREFACE

I, **Thomas James Rowe** declare that:

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A_B	=	A to B horizon redistribution rate
ABRESP	=	Fraction of soil water above DUL that drains from the A horizon into the B horizon of a soil
ACRU	=	Agricultural Catchments Research Unit
AMS	=	Annual Maximum Series
APAN	=	Daily A-pan equivalent evaporation (mm)
ARC-ISCW	=	Agricultural Research Council's Institute for Soil, Climate and Water
ASCE	=	American Society of Civil Engineers
AUTOSOILS	=	Computer programme which translates information from the Land Type databases into soils information needed by the *ACRU* model
BFRESP	=	Fraction of soil water above DUL that drains from the B horizon of the soil into the intermediate groundwater zone
CAPA	=	Catchment Parameter
CAY	=	Crop Coefficient
CCS	=	Continuous Simulation System
CN	=	Curve Number
COFRU	=	Coefficient of Baseflow Response
COIAM	=	Coefficient of Initial Abstraction
COMPOVEG	=	Database containing land cover specific *ACRU* variables
CONST	=	Fraction of plant available water where actual evaporation drops below maximum evaporation
COST	=	The European Cooperation in Science and Technology
CSM	=	Continuous Simulation Modelling

CWRR	=	Centre for Water Resources Research
DEPAHO	=	Depth of the A horizon (m)
DEPBHO	=	Depth of the B horizon (m)
DFE	=	Design Flood Estimation
DUL	=	Drained Upper Limit
DWS	=	Department of Water and Sanitation
E	=	Actual Total Evaporation
E_m	=	Maximum Total Evaporation
E_r	=	Reference Potential Evaporation
Es	=	Soil Water Evaporation
Et	=	Plant Transpiration
EVTR1	=	Evapotranspiration option 1
EVTR2	=	Evapotranspiration option 2
GEV	=	General Extreme Value
HEC-HMS	=	The Hydrologic Engineering Center – Hydrologic Modeling system
HRU	=	Hydrological Research Unit
HRUs	=	Hydrological Response Units
IDF	=	Intensity-Duration-Frequency
ITEXT	=	Eleven texture classes defined in the *ACRU* model
IUGG	=	The International Union of Geodesy and Geophysics
JPV	=	Joint Peak-Volume
Ks	=	Saturated hydraulic conductivity
KZN	=	KwaZulu-Natal
LEV1	=	Log-Extreme Value Type 1

LN	=	Log Normal
LP-III	=	Log Pearson Type III
LRH	=	Lag-Routed Hydrograph
MAF	=	Mean Annual Flood
MAP	=	Mean Annual Precipitation
MAR	=	Mean Annual Streamflow
MIPI	=	Midgley and Pitman
NLC, 2000	=	National Land Cover dataset for the year 2000
NRF	=	National Research Foundation
PAW	=	Plant Available Water
PCSUCO	=	Percentage surface cover (mulch, litter, *etc*.)
PDM	=	Probability Distributed Model
PO	=	Porosity
PRMS	=	Precipitation-Runoff Modeling System
PUB	=	Predictions in Ungauged Basins
PWP	=	Permanent Wilting Point
QCD	=	Quinary Catchments Database
QFRESP	=	Quick Flow Response Coefficient
RAINFALL	=	Daily rainfall (mm)
ReFH	=	Revitalized Flood Hydrograph model
REFSSA	=	Regional Estimation of Extreme Flood Peaks by Selective Statistical Analyses
RMF	=	Regional Maximum Flood
ROOTA	=	Fraction of active root mass in the A horizon of the soil

S	=	Soil Water Deficit
SANBI	=	The South African National Biodiversity Institute
SANRAL	=	The South Africa National Roads Agency Limited
SBM	=	String-of-Beads Model
SCS	=	Soil Conservation Service
SCS-SA	=	South African adaptation of the SCS model
SCWG	=	Soil Classification Working Group
SDF	=	Standard Design Flood
SIRI	=	Soil and Irrigation Research Institute
SMDDEP	=	Critical Response Depth of the Soil
STORMF	=	Stormflow
T_c	=	Time of Concentration
UKZN	=	The University of KwaZulu-Natal
UQFLOW	=	Same Day Response Fraction
USACE	=	U.S. Army Corps of Engineers
USGS	=	U.S. Geological Survey
VEGINT	=	Interception loss (mm.rainday^{-1}) by vegetation
ψ	=	Critical Soil Water Content
Θ	=	Soil Water Content

1. INTRODUCTION

Design Flood Estimation (DFE) is essential in the planning and design of hydrological structures. This involves the assessment of flood risk by associating a flood event with a probability of exceedance or return period (Smithers, 2012; Kang *et al.*, 2013). Alexander (2002) highlighted the need for alternative DFE procedures, or the development and improvement of conventional DFE techniques, after severe flooding in Southern Africa in 1999 and 2000. During these severe floods hundreds of lives were lost and thousands of people had to be placed in refugee camps. Furthermore, in terms of infrastructure more than 200 bridges failed or were substantially damaged, road networks were extensively impaired and the recovery cost of communication infrastructure in both Mozambique and South Africa was in the order of R1000 million, which were costs these countries could not afford (Alexander, 2002). Smithers (2012) supports the comments of Alexander (2002) after flooding in the Western Cape in 2005 and the Free State and Eastern Cape in 2011. Alterations in rainfall patterns, generally attributed to climate change or more recently global change (Kusangaya *et al.*, 2014), further complicates the estimation of design floods and reinforces the need for improved approaches to DFE. Additionally, after a review of flood frequency estimation techniques and approaches in Europe, The European Cooperation in Science and Technology (COST, 2013) highlighted that in most countries flood frequency estimation is currently being undertaken using models based on the assumption of stationarity, *i.e.* in terms of historical records of flood flows or rainfall. This emphasises the need to consider the effects of environmental change when estimating design floods.

DFE techniques for most countries can be grouped into two broad groups, which generally include approaches based on the statistical analysis of observed peak discharges and approaches based on event modelling or Continuous Simulation Modelling (CSM) using rainfall-runoff techniques (Boughton and Droop, 2003; Pathiraja *et al.*, 2012; Smithers, 2012). Approaches to DFE in South Africa are similarly classified into two groups based on (i) the analysis of observed flood peaks and (ii) rainfall-runoff based techniques (Smithers and Schulze, 2002; Smithers, 2012). In this document several methods based on the frequency analysis of flood peaks and rainfall-runoff based techniques, within South Africa, are reviewed and evaluated. The numerous benefits of the rainfall-runoff CSM approach to DFE are highlighted within much of the literature including, *inter alia*, Calver and Lamb (1995);

Cameron *et al.* (1999); Smithers and Schulze (2002); Boughton and Droop (2003); Chetty and Smithers (2005); Brocca *et al.* (2011); Pathiraja *et al.* (2012); Smithers (2012); Smithers *et al.* (2013), both locally and internationally, emphasising the potential of CSM to overcome many of the limitations of event-based models as well as being able to improve the prediction of extreme flood events in ungauged catchments, a challenge often faced by hydrologists and engineers (Hrachowitz *et al.*, 2013). Examples of these benefits include the fact that actual climatic information is input into the model at specified time steps and therefore the antecedent soil moisture is accounted for and not estimated or averaged. Furthermore, calibration of models is avoided and results are based on an increased understanding of hydrological processes and catchment conditions. Consequently, predictions in ungauged basins are more reliable and scientific, *i.e.* model parameters are linked to catchment characteristics and may therefore be transferred to ungauged catchments (Hrachowitz *et al.*, 2013). Lastly the method can account for the non-stationarity of the environment, *i.e.* in terms of land use/land cover change as well as changes in climate. Therefore as alluded to by COST (2013) the assumption of stationarity is avoided.

In identifying the benefits and potential of CSM, this document focuses on the progress towards a CSM approach to DFE in South Africa. The model selected is the *ACRU* model (Schulze, 1995) since it has been successfully used in the past and is adapted to South African conditions. Currently, however, one of the most popular rainfall-runoff techniques used in practise is the SCS-SA adaptation (Schmidt and Schulze, 1987a) of the widely used SCS (1956) model. A detailed review of both the SCS-SA and *ACRU* models is performed, identifying some of the major similarities and differences between the models. The review identifies that in terms of land cover information, the land cover classification used in the SCS-SA model accounts for different land management practices and hydrological conditions, which are not accounted for in the *ACRU* land cover classification schemes. Since the runoff response variables used in the original SCS model were derived from observations, and the SCS-SA model is an accepted method of DFE in small catchments in South Africa (Schmidt and Schulze, 1987a; Schulze *et al.*, 2004; SANRAL, 2013), it was assumed in this study that the design runoff volumes simulated by the SCS-SA model are reasonable, and that the relative changes in design runoff volumes simulated by the SCS-SA model as a consequence of changes in land management practices or condition are also reasonable. Based on these assumptions, the aim of this study was to investigate how design volumes simulated by the SCS-SA model for various land management practices or conditions could be simulated by the *ACRU* model, and to derive classes in the *ACRU* classification schemes for land management practice and hydrological condition. This is achieved by investigating to which variables the model is most sensitive in terms of DFE, and subsequently adjusting relevant variables in the *ACRU* model to represent the change in management practice or condition, as represented in the SCS-SA model for SCS-SA soil response groups.

The specific objectives of this study are to: (i) briefly review DFE techniques currently used in South Africa, (ii) highlight why a CSM approach to DFE should be adopted in South Africa, (iii) investigate how to represent SCS-SA soil groups and land cover classes in the *ACRU* model, and (iv) identify trends and develop rules and formulas that may be consistently applied in the *ACRU* model in order to simulate relative hydrological impacts of management practices and hydrological conditions which are similar to those estimated using the SCS-SA model.

2. DESIGN FLOOD ESTIMATION IN SOUTH AFRICA

In South Africa the methods used to estimate design floods may be categorised into two groups as shown in Figure 2.1: (i) analysis of observed flood peaks and (ii) rainfall-runoff based techniques (Smithers and Schulze, 2002; Smithers, 2012). The following sections will review these DFE techniques beginning with approaches based on the analysis of streamflow, followed by rainfall based methods.

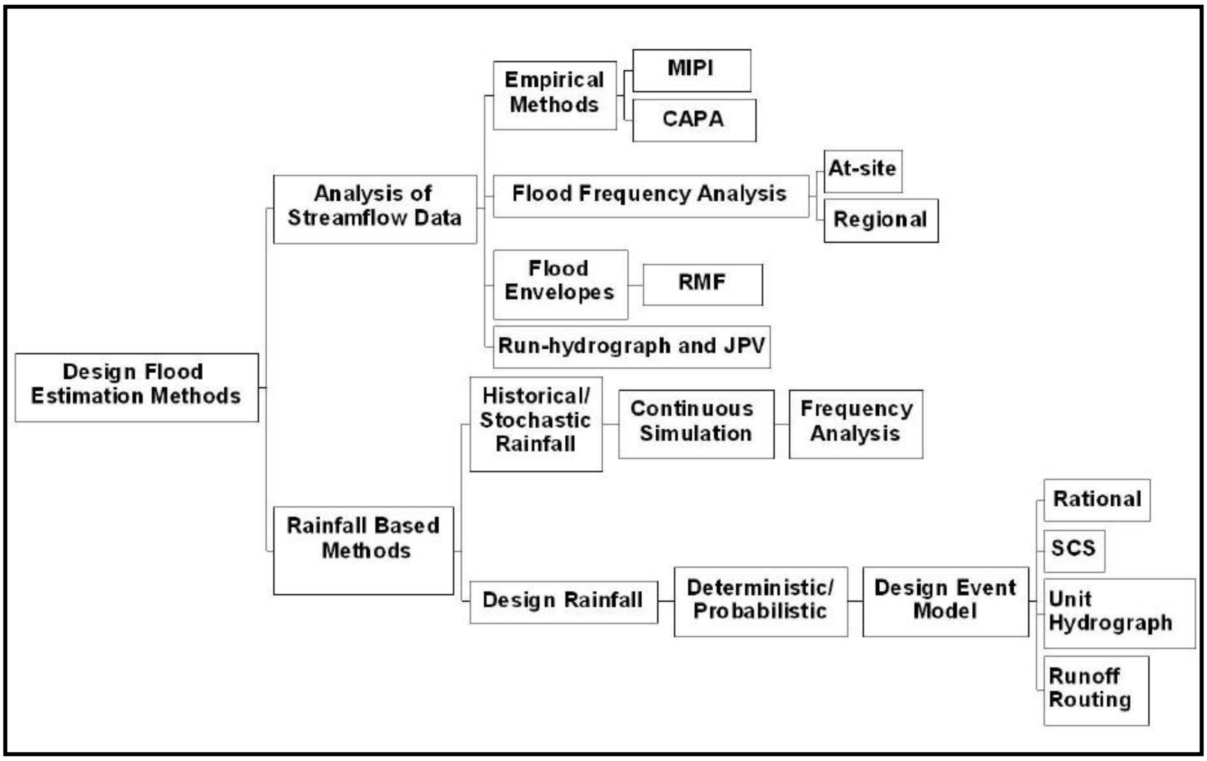


Figure 2.1 DFE methodologies within South Africa (Smithers, 2012)

2.1 Analysis of Streamflow Data

When adequate streamflow data is accessible, several approaches are available to estimate design floods, as summarised in Figure 2.1. Each of these approaches is reviewed briefly in the sections to follow.

2.1.1 Empirical methods

Empirical methods or empirical formulae use algorithms to relate peak discharge to catchment size and other climatic and physiographic catchment descriptors, *e.g.* such as the MIPI and CAPA methods (Smithers, 2012). The MIPI and CAPA methods are described as follows:

(i) The Midgley and Pitman (MIPI) method: The MIPI method developed by Midgley and Pitman (1967), is an improved version of the earlier method proposed by Roberts which used the Hazen distribution to determine catchment coefficients/constants (van Vuuren *et al.*, 2013). The MIPI method is an empirical probabilistic method that relates the design peak discharge of a catchment, determined from frequency analyses of the Annual Maximum Series (AMS) at 83 flow-gauging stations in South Africa using a Log-Extreme Value Type 1 (LEV1) distribution, to the geographical location and area of that catchment (van Vuuren *et al.*, 2013). Characteristics of the geographical location of a catchment which were included are the topography, rainfall characteristics, soils, drainage patterns and plant cover. All of these characteristics were used to divide South Africa into seven homogeneous flood regions, each with an empirically determined regional catchment coefficient/constant (SANRAL, 2013). Gericke and du Plessis (2013) state that research has shown the LEV1 distribution to be less satisfactory in comparison to the Hazen, Log Normal (LN) and Log Pearson Type III (LP-III) distributions, even though the LEV1 distribution has a sounder theoretical basis. The MIPI method, however, is simple to apply and produces reasonable design flood estimates (van Vuuren *et al.*, 2013). Midgley and Pitman (1971) also developed an empirical-deterministic method to estimate flood peaks incorporating Mean Annual Precipitation (MAP), the hydraulic length of the catchment, the average slope of the main watercourse and the distance to the catchment centroid, in addition to catchment area and the regional catchment coefficients/constants (van Vuuren *et al.*, 2013). According to Gericke and du Plessis (2013), the empirical-deterministic method produces results comparable to those obtained with the synthetic unit hydrograph approach.

(ii) The Catchment Parameter (CAPA) method: The CAPA method developed by McPherson (1983) is an index-flood type approach, where the Mean Annual Flood (MAF) is used as the flood index (Gericke and du Plessis, 2013). The method empirically relates the MAF to four catchment characteristics which includes the catchment area, MAP, average catchment slope and catchment shape (van Vuuren *et al.*, 2013). Pegram and Parak (2004) and Gericke and du Plessis (2013), however, note that the estimated MAF is particularly sensitive to catchment area.

Cordery and Pilgrim (2000), Gericke and du Plessis (2013) and SANRAL (2013) caution on the use of empirical methods, particularly if they were not calibrated from the catchment in question, and suggest that they should only be used to check other methods. More recently, Nortje (2010) developed an empirical Regional Estimation of Extreme Flood Peaks by Selective Statistical Analyses (REFSSA) method for two large catchments in South Africa. However, Nortje (2010) cautions against the use of the method outside these areas and acknowledges that the method needs further assessment and refinement.

2.1.2 Flood frequency analysis

Another common technique used to estimate design floods is to perform a frequency analysis of observed flow data, where an adequate record length and quality of data is available at the site of interest. This may be performed (i) at a specific site, or (ii) a regional approach may be implemented (Smithers, 2012). Performing a frequency analysis on observed peak discharges, both at site and utilising a regional approach, involves the selection and fitting of an appropriate theoretical probability distribution to the observed data. Several probability distributions are available and may be fitted with specific mathematical techniques such as the Method of Moments, L-Moments, the Maximum Likelihood Procedure, Probability Weighted Moments, Bayesian Inference and non-parametric methods (ASCE, 1996; Smithers and Schulze, 2000; Chebana *et al.*, 2012; Kim *et al.*, 2012). The most commonly used probability distributions in South Africa are the LP-III and the General Extreme Value (GEV) distributions (Görgens *et al.*, 2007). Internationally the most commonly used distribution is generally the LP-III distribution (Alexander, 2002; Smithers, 2012). A limitation of the approaches based on flood frequency analysis includes the assumption of data stationarity. Historical observed flood data, however, may not be stationary as a result of changes in climate and changes in land cover/use within a catchment or region (Gericke and du Plessis, 2013).

The two approaches to flood frequency analysis are summarised as follows:

(i) At-site Analysis: A frequency analysis of observed peak discharges from a single site is performed on streamflow data from the catchment under investigation. Generally however, regional flood frequency analyses are preferred (Kjeldsen *et al.*, 2002; Nortje, 2010; Haile, 2011; Smithers, 2012), for several reasons as detailed below.

(ii) Regional Approach: Regional flood frequency analyses generally result in more reliable design estimates due to, *inter alia*, a greater representation of flood data being utilised from homogeneous regions, *i.e.* utilising data from several sites to estimate the frequency distribution of observed data at each site (Kachroo *et al.*, 2000; Malekinezhad *et al.*, 2011; Smithers, 2012). A regional approach generally assumes that the standardised variate has the same distribution at every site within a selected relatively homogeneous region. Thus, data from the region may be combined to produce a single regionalised distribution, after appropriate site-specific scaling of the data (Cunnane, 1988; Hosking and Wallis, 1997; Haile, 2011; Smithers, 2012). Flow data at a site is often not available or seldom sufficient, *e.g.* in terms of record length and quality of record, to confidently estimate design floods. Thus, the regionalised approaches to flood frequency estimation can be used at a site where no, or inadequate, flow data is available (Smithers, 2012). Thus, much of the literature promotes the use of regional flood frequency analyses, based on the advantages of the approach, including those mentioned above (*e.g.* Cunnane, 1988; Cordery and Pilgrim, 2000; Kjeldsen *et al.*, 2002; Nortje, 2010; COST, 2013; Gericke and du Plessis, 2013; Nguyen *et al.*, 2014; Nobert *et al.*, 2014).

2.1.3 Flood envelopes

In the flood envelopes approaches, the largest observed discharges are generally plotted against catchment area and regionalised upper envelopes to the observations are drawn (Smithers, 2012). The HRU (1972) established a set of regionalised maximum observed flood peak envelopes for South Africa, and Kovacs (1988) subsequently developed comprehensive Regional Maximum Flood (RMF) envelopes for South Africa, Swaziland, Namibia and Zimbabwe (Smithers, 2012). The RMF method is generally more suited to medium and large sized catchments. Görgens *et al.* (2007) identified that the envelopes are in need of updating with recent flood peak observations in certain areas exceeding the RMF envelope values suggested by Kovacs (1988). One shortcoming, highlighted by Nortje (2010), is that the RMF method has no exceedance probability associated with the RMF values. However, Kovacs (1988) estimated the return period of the RMF to be approximately 200 years. Pegram and Parak (2004) attempted to determine a return period for the RMF and their results indicate that it would be reasonable to assume the RMF to have a return period in the order of 200 years.

2.1.4 Run-hydrograph and Joint Peak-Volume methodology

The run-hydrograph method, developed by Hiemstra and Francis (1979), summarises the family of characteristic peak and volume discharges for a given catchment, for specific return periods (Pegram and Parak, 2006). The method is based on the joint probability analysis of flood volume and flood peak pairs from individual events for recorded data from 43 catchments around South Africa (Pegram and Parak, 2006). Ultimately, the run-hydrograph method produces peak-volume hydrograph families with an equal probability of jointly being exceeded, but with varying hydrograph shapes, *i.e.* different peak and volume discharge combinations with the same exceedance probability (Pegram and Parak, 2006). Following the development of the run-hydrograph method by Hiemstra and Francis (1979), the method received little attention until Görgens (2007) further developed the run-hydrograph method, which is appropriately renamed the Joint Peak-Volume (JPV) design flood methodology. The JPV method considers both flood peaks as well as flood volumes, which are particularly important in the design and safety evaluation of medium to large dams. Görgens (2007) states that the objective of the JPV approach is to provide hydrological and engineering practitioners with modernised procedures and tools that produce flood volume exceedance frequencies empirically linked to flood peak magnitudes at a regional scale. Therefore, for any design flood peak estimated from any of the various methods available, the exceedance frequency of any design flood hydrograph volume may be obtained by the practitioner. Görgens (2007) used regional pooling techniques based on either the K-regions as delineated by Kovacs (1988), the veld zone groups as delineated by the HRU (1972), as well as a customised technique to group "hydrologically similar" catchments. Thus, the JPV design flood methodology can be applied in ungauged catchments. Design floods, estimated using the JPV methodology and the regionally pooled approach with both the GEV or LP-III distribution, were compared to floods computed by the synthetic unit hydrographs developed by the HRU

(1972) and against at-site probabilistic estimates by Görgens (2007). The results indicate that the regionally pooled approach with the GEV distribution generally performed better than both the synthetic unit hydrographs and the regionally pooled LP-III distribution. In some catchments, however, the JPV method over-estimated flood peaks, which Görgens (2007) was able to correct using simple adjustments based on the characteristics of a donor catchment.

2.2 Rainfall Event Based Methods

In many cases in South Africa, as well as internationally, observed streamflow data is not available or the records are not adequate or sufficient for analysis using one of the above mentioned approaches, *i.e.* in terms of record length, missing records or quality of the data. In addition, approaches based on the analysis of streamflow generally assume catchment responses are stationary, *i.e.* catchment conditions and climate remain unaltered, which is often not the case and potentially reduces the applicability of the use of streamflow records for direct frequency analysis. Alternatively, rainfall based techniques can include the physical characteristics of a catchment and therefore catchments can be modelled for historical, current or expected future conditions (Smithers, 2012). Furthermore, there are generally more rainfall stations with longer records than flow gauging stations, therefore rainfall based approaches to DFE may overcome the aforementioned issues associated with inadequate or insufficient streamflow records. Rainfall based approaches are deterministic in nature since rainfall is translated into a flood (Smithers and Schulze, 2002; Smithers, 2012). Storm runoff volumes and peak discharges are seldom available for small catchments in southern Africa (Schmidt and Schulze, 1987a; Smithers, 2012) and therefore estimates of design flood volumes and peak discharges are frequently estimated using event-based rainfall-runoff models. As depicted in Figure 2.1, rainfall based techniques are divided into two groups (i) event-based approaches using design rainfall and (ii) CSM using historical/stochastic rainfall series.

Currently, three design event-based methods are widely used in South Africa: (i) the Rational method, (ii) Unit Hydrograph technique, and (iii) the SCS-SA approach (Smithers and Schulze, 2002; Pegram and Parak, 2004; SANRAL, 2013; van Vuuren *et al.*, 2013). Design event models estimate design runoff depths, volumes or peak discharges from individual design rainfall events for a given duration and selected return period (Smithers, 2012). Therefore, the return period of a design runoff event is assumed to be equal to the return period of the design rainfall used, which is a major limitation of event-based models (Schmidt and Schulze, 1987a; Schulze, 1989; Smithers and Schulze, 2002; Smithers, 2012). This limitation is as a result of the event-based models generally not being able to account for evapotranspiration, infiltration, catchment storage, soil moisture and water movement within the soil, *e.g.* the soil moisture prior to design rainfall events is assumed, not directly accounted for (Hernandez *et al.*, 2000; Coustau *et al.*, 2012). According to Pathiraja *et al.* (2012), the above properties are commonly pooled together into a single set of "loss" parameters, which are often adjusted through calibration. The CSM approach, on the other hand, explicitly accounts for the antecedent soil moisture prior to large events, using continuous soil water budgeting (Schulze, 1995; Smithers and Schulze, 2002; Smithers, 2012). This is a major advantage of the CSM approach over traditional event-based approaches. The event-based rainfall-runoff models depicted in Figure 2.1 are briefly described in the sections to follow. This is followed by a detailed review of CSM for DFE.

2.2.1 Rational method

Pegram and Parak (2006) state that the Rational method is one of the most well-known and widely used methods to determine the peak discharge of a catchment from rainfall events. The method has been extensively used due to its ease of use and simplicity, for which it has also received extensive criticism (Pegram and Parak, 2006). The method is said to oversimplify the complex hydrological processes of flood generation using only three parameters; the catchment area, design storm rainfall intensity and a runoff coefficient which defines the proportion of precipitation contributing to runoff generation. Despite the criticism, however, the method remains one of the most popular peak flood estimation techniques utilised by practitioners (Pegram and Parak, 2006; SANRAL, 2013; van Vuuren *et al.*, 2013).

The HRU (1972) limited the use of the Rational method to small catchments (<15km^2) in South Africa, where the method was applied in a deterministic manner, *i.e.* the probabilistic nature of runoff coefficients was not taken into account. Alexander (2002), however, believed that the limitation of the Rational method to small catchments was too conservative and showed that the method is also applicable to larger catchments. It was cautioned, however, that sound engineering experience and judgment was required to obtain accurate results using the Rational method, particularly in the selection of runoff coefficients (Pegram and Parak, 2006). Pegram and Parak (2006) suggest the use of a probabilistic approach when utilising the Rational method for DFE, where the rainfall intensity, *i.e.* design rainfall depth divided by the Time of Concentration (T_c), and the runoff coefficient are associated with a probability of exceedance. This is because no unique combination of catchment conditions exists for a design rainfall event, as in the case with a historical event (Pegram and Parak, 2006). Design rainfall values for South Africa are generally readily available from suitable Intensity-Duration-Frequency (IDF) relationships of design storms (Pegram and Parak, 2006). However, estimating a design or return period runoff coefficient remains a major uncertainty in the application of the Rational method. Alexander (2002) developed a regionally calibrated Rational method, termed the "Standard Design Flood" (SDF), applicable to catchments ranging in size from 10km^2 to 40 000km^2. The SDF method has been shown to be over-conservative, resulting in the wastage of resources when designing engineering structures such as dam spillways (Görgens, 2002). In addition, Van Bladeren (2005) reported on problems associated with the SDF method and suggested several refinements to the method. Further development and/or assessment of the probabilistic Rational method have also been investigated by, *inter alia*, Pilgrim and Cordery (1993), Pegram (2003), Pegram and Parak (2004), Pegram and Parak (2006) and Gericke (2010). Probabilistic application of the Rational method is generally only recommended for use in the evaluation of other methods, because of the difficulty in adequately assigning a single regionally calibrated runoff coefficient to a specific location (Pegram and Parak, 2006). An additional limitation of the Rational method is that complete hydrographs are not generated and only peak discharges are computed.

2.2.2 Unit Hydrograph technique

A Unit Hydrograph is defined as the direct runoff hydrograph from a storm with a unit depth of effective rainfall (Weaver, 2003). Effective rainfall is the portion of total rainfall that contributes directly to streamflow through surface runoff, *i.e.* excluding that portion of the rainfall that is intercepted and which infiltrates into the soil (Weaver, 2003). The principle of the Unit Hydrograph approach is based on the concept that each catchment has a characteristic hydrograph "signature" that does not change in shape, unless the catchment characteristics change (Weaver, 2003). Therefore, the Unit Hydrograph derived for a catchment, from observed data, may be used to determine flood hydrographs for actual or design rainfall events by multiplying the discharge ordinates of the unit hydrograph by the effective/excess rainfall from the observed or design rainfall. The HRU (1972) developed a Unit Hydrograph method for South Africa, using data from 92 gauges across the country with catchment areas ranging from 21 to 22 163km^2 (Smithers and Schulze, 2002). Dimensionless one hour Unit Hydrographs were developed for nine veld zone types identified in South Africa and a co-axial diagram was simultaneously developed to estimate storm losses for each of the nine zones (Smithers and Schulze, 2002). Smithers and Schulze (2002) identify two limitations of the Unit Hydrograph approach: (i) the method assumes that catchment responses are linear and consequently may not be accurate for estimating large floods (Smithers and Schulze, 2002), and (ii) the method also assumes spatial uniformity of rainfall. An advantage of the technique, however, is that the entire hydrograph is estimated (Smithers and Schulze, 2002). No refinement or further development of the Unit Hydrograph approach in South Africa has occurred since its development by the HRU (1972) in the 1970's (Smithers and Schulze, 2002).

2.2.3 Runoff routing

As flood waves move downstream in a river or channel, or are routed through a dam, the flood hydrograph is altered in two ways: (i) attenuation of the flood wave occurs, *i.e.* the magnitude of the flood peak changes, and (ii) translation of the flood hydrograph takes place, *i.e.* the timing of the flood peak changes (USACE, 1994). Flood routing is used to estimate the alterations to a flood wave as it moves through a river reach or impoundment. Flood routing techniques are generally classified as hydraulic or hydrological. Hydraulic methods, although more accurate, are complex and data intensive, while hydrological methods are relatively simple and reasonably accurate (Choudhury *et al.*, 2002). Bauer and Midgley (1974) developed a Lag-Routed Hydrograph (LRH) method for South Africa based on the Unit Hydrograph method using Muskingum routing coefficients. Gericke and du Plessis (2013) believe that the Lag-Routed Hydrograph and Unit Hydrograph methods are not independent methods, and hence the Lag-Routed Hydrograph method cannot be used as an independent check of the more detailed Unit Hydrograph technique. The Muskingum model and derivatives thereof are some of the most frequently used hydrological flood routing methods because of their simplicity. More recently, Smithers *et al.* (2007) obtained reasonable results from a pilot study in the Thukela Catchment using the Muskingum-Cunge (Cunge, 1969) method which may be used to route floods through ungauged catchments.

2.2.4 SCS approach

The SCS model, developed by the Soil Conservation Service (SCS, 1956), is a deterministic model that converts a depth of rainfall into a runoff volume and/or a peak discharge (Pegram and Parak, 2004). The calculation of runoff depth is computed from a rainfall depth based on a parameter representative of the catchment runoff response characteristics (Schmidt and Schulze, 1987a). The peak discharge and storm hydrograph are generated by superpositioning of incremental triangular unit hydrographs according to the distribution of stormflow depth over time, as determined from the time distribution of rainfall intensity and the stormflow response characteristics of the catchment, *i.e.* the catchment lag (Schulze *et al.*, 1992). The original SCS Curve Number (CN) approach and adaptations thereof are still widely used for estimating storm runoff from rainfall (Kannan *et al.*, 2008; Ajmal *et al.*, 2015; IUGG, 2015). Its wide use is linked to the ability of the method to account for the physical characteristics of a catchment and the antecedent soil moisture. In terms of the latter, however, antecedent moisture was generally dealt with in very gross terms (Smithers and Schulze, 2002).

In South Africa, extensive refinement and further development was done on the SCS method and the technique was adapted for South African conditions by, *inter alia*, Schulze and Arnold (1979), Schmidt and Schulze (1987a) and Schmidt and Schulze (1987b), and the adapted version termed SCS-SA. One of the strengths of the SCS-SA model was the development of a procedure to account for typical antecedent soil moisture conditions, using the median condition method, and for estimating design runoff by the joint association of rainfall and antecedent conditions, using the joint association method (Schmidt and Schulze, 1987a). The median condition method is used to adjust the initial CNs, *i.e.* derived from the soil properties, land cover and land management practices, to a final CN using the Hawkins (1978) equation. The Hawkins (1978) equation computes the water balance to calculate the change in storage within a soil, over a 30 day period leading up to a design rainfall event. The change in storage was simulated using the *ACRU* model for 712 homogeneous hydrological response zones and 27 combinations of soil and vegetation properties (Schmidt and Schulze, 1987a). In terms of the median condition approach, the 50th percentile, *i.e.* "average", change in soil moisture is used to adjust the initial CN to a final CN. One of the limitations of this approach, however, is the inherent assumption that the T-year return period rainfall event produces the T-year return period flood (Schmidt and Schulze, 1987a). The joint association approach, alternatively, performs a frequency analysis on the simulated discharges of the five biggest events in each year of record, and therefore accounts for the joint association of rainfall and runoff, where the second, third or fourth largest rainfall event in each year may produce the largest flood.

Schmidt and Schulze (1987a) developed a new catchment lag equation, used in the calculation of peak discharge, termed the Schmidt-Schulze lag equation. Estimating catchment lag, however, remains a challenge (Gericke, 2011). More recently, the SCS-SA model has been updated to be compatible with the Windows operating systems along with some additional refinements (Schulze *et al.*, 1992; Schulze *et al.*, 2004; Schulze, 2012). It may be argued that the success of the results from the soil moisture accounting procedures used in SCS-SA, which simulated hydrological responses for a range of land covers and soils for 30 days prior to large rainfall events, lead to the identification of the potential for a CSM approach to DFE in South Africa. This appropriately leads on to the next and final rainfall-based method reviewed, as depicted in Figure 2.1, CSM.

2.3 Continuous Simulation Modelling

Schulze (1989), Smithers and Schulze (2002) and Smithers (2012) motivate for a CSM approach to DFE in South Africa, stating that continuous simulation models attempt to represent the major processes which convert rainfall into runoff. Historical rainfall records, or stochastically generated rainfall sequences, can be used to generate outflow hydrographs and these simulated flows may then be subjected to standard frequency analysis techniques.

Schulze (1989), Smithers and Schulze (2002) and Smithers (2012) list several reasons why a CSM approach is needed:

(i) the estimation of accurate design flood values requires long periods of flow records,
(ii) analysis of streamflow data is generally limited in South Africa due to streamflow data often being unavailable, or containing errors and inconsistencies, while the assumptions of homogeneity and stationarity of streamflow data are often not valid;

(iii) rainfall records, on the other hand, are available from a denser network of gauges, are generally of better quality and have longer record lengths compared to streamflow data; and
(iv) the limitation of event-based models, with the assumption that the exceedance probability of the flood is related to the exceedance probability of the input rainfall, is not applicable when using a CSM approach, *i.e.* a frequency analysis is performed directly on simulated flows.

Schulze (1989), Smithers and Schulze (2002) and Smithers (2012) refer to several other studies including Boughton and Hill (1997), Rahman *et al.* (1998) and Reed (1999), supported by, *inter alia*, Boughton and Droop (2003), Brocca *et al.* (2011) and Pathiraja *et al.* (2012), all motivating that a CSM approach overcomes many of the limitations of event-based methods, due to the following:

(i) actual rainfall records are used and not synthetic storms, therefore critical storm duration is not an issue;
(ii) complete hydrographs are generated and not only peak discharges;
(iii) assumptions about losses are avoided, as losses are explicitly simulated by the use of a verified rainfall-runoff model;
(iv) the antecedent soil moisture is accounted for explicitly in the model and therefore any subjectivity in attempting to account for antecedent conditions is removed and, as stated above, a frequency analysis is performed on the simulated flows output by the model, and consequently the exceedance probability of the output is not assumed to be the same as that of the input rainfall.

However, several potential drawbacks of the method are also identified by Schulze (1989), Smithers and Schulze (2002) and Smithers (2012), again referencing, *inter alia*, Boughton and Hill (1997), Rahman *et al.* (1998) and Reed (1999):

(i) adequately modelling the soil moisture balance is challenging, *i.e.* obtaining input data at the correct temporal and spatial scale may be difficult and the number of variables to calibrate may be extensive;
(ii) rapid events that peak and fall quickly may be poorly simulated if the modelling time scale is too coarse;
(iii) the methods are often data intensive, resulting in significant time and effort being expended to obtain and prepare input data; and finally

(iv) significant hydrological expertise may be required to determine parameter values to ensure that historical hydrographs are adequately simulated.

In South Africa, CSM has been used successfully in a number of studies with reasonable results (Smithers *et al.*, 1997; Smithers *et al.*, 2001; Chetty and Smithers, 2005; Smithers *et al.*, 2007; Smithers *et al.*, 2013). Furthermore, with improvements in computational abilities and current technology available, many of the limitations mentioned above may be overcome or minimised. Therefore realising the need and potential for a CSM approach to DFE in South Africa, as reviewed from the literature above, the following sections will analyse CSM in more detail. Both international trends and local developments in South Africa and what needs to be done to further improve and develop a suitable CSM approach are discussed.

2.3.1 International trends

The potential of CSM in DFE has been highlighted by several studies both locally and internationally including, *inter alia*, Calver and Lamb (1995); Cameron *et al.* (1999); Smithers and Schulze (2002); Boughton and Droop (2003); Chetty and Smithers (2005); Brocca *et al.* (2011); Pathiraja *et al.* (2012); Smithers (2012); Bellot and Chirino (2013); COST (2013); Smithers *et al.* (2013) and Ball *et al.* (2015). Boughton and Droop (2003) identified an increasing interest in CSM for DFE within several countries. For example, in Australia the Continuous Simulation System (CCS) for DFE has been developed (Boughton and Droop, 2003). In the USA, several continuous simulation systems are in use, such as the Stanford Watershed Model and descendants thereof, including the Hydrocomp model which is one of the most well-known continuous simulation models utilised in the USA (Boughton and Droop, 2003). The U.S. Geological Survey (USGS) Precipitation-Runoff Modeling System (PRMS) is a continuous simulation distributed parameter model for use in small forested headwater catchments (Boughton and Droop, 2003). In Europe, models such as TOPMODEL, the TATE model, the Probability Distributed Model (PDM) and the SHE model are all continuous simulation models that have been developed (Boughton and Droop, 2003). Boughton and Droop (2003) also make reference to the *ACRU* continuous simulation approach utilised in South Africa for DFE, which will be elaborated on in the sections to follow.

CSM is receiving increasing attention and has been included in many more recently developed, rainfall-runoff models internationally. For example in the Revitalized Flood Hydrograph (ReFH) model, which consists of three main components including: a loss model – converting total rainfall into effective rainfall; a routing model and a baseflow model (Kjeldsen, 2007). The Hydrologic Engineering Center – Hydrologic Modeling System (HEC-HMS) includes a continuous simulation modelling approach to determine the soil moisture status, using a one-layer or more complex five-layer soil moisture method (USACE, 2008). Pathiraja *et al.* (2012) state that continuous simulation modelling for DFE is increasingly becoming a viable alternative to traditional event-based methods. Pathiraja *et al.* (2012) experimented with a continuous simulation model on 45 gauged catchments in the Murray-Darling Basin in Australia, in order to identify the importance of accurately accounting for antecedent soil moisture in flood modelling. Furthermore, Hrachowitz *et al.* (2013) reviewed a decade of Predictions in Ungauged Basins (PUB) and highlighted the necessity to shift away from the traditional empirical approaches to DFE, with a new focus on physical and or conceptual approaches where increasing understanding of hydrological processes is incorporated into hydrological models. In other words, variables are assigned to model parameters based on the actual physical properties of the catchment, avoiding the parameter fitting and subsequent equifinality associated with traditional calibration/empirical methods (Hrachowitz *et al.*, 2013).

Brocca *et al.* (2011) emphasise that the large number of parameters incorporated in rainfall-runoff models, including continuous simulation models, can increase model uncertainty. Therefore, several studies highlight the importance of collecting new and possibly more accurate data that represents the internal states of the model, in order to reduce uncertainties in hydrological modelling calibration and validation (Brocca *et al.*, 2011). Once the model has been validated and calibrated, the model can be used with historical climate records to yield flood frequency estimates (Brocca *et al.*, 2011). If model parameters can be related to the catchment characteristics, it is possible to transfer model parameters to similar ungauged catchments (Calver and Lamb, 1995). The possibilities and importance of CSM, especially the use of physical-conceptual models, is emphasised by Hrachowitz *et al.* (2013) who believe that models based on increasing knowledge and understanding of hydrological processes and their interactions at various scales are essential to improving predictions in ungauged basins.

Having evaluated CSM within the international literature, the next section contains a review of CSM within South Africa. This is essential to identify: (i) what has been achieved to date, and (ii) what the recommendations are for the future.

2.3.2 Local developments

In South Africa, a preliminary assessment of a continuous simulation modelling approach to DFE has been undertaken by Smithers *et al.* (2007) for the Thukela Catchment. The continuous simulation model selected was the daily time-step *ACRU* agrohydrological model (Schulze, 1995), which has been used previously with reasonable results by Smithers *et al.* (1997) and Smithers *et al.* (2001). Some of the objectives of the study by Smithers *et al.* (2007) were to investigate: (i) the appropriate scale at which continuous simulation modelling should take place; (ii) the level of soil and land cover information needed for use with the CSM approach; and (iii) what effect the spatial variability of rainfall has on the runoff depth generated from a catchment. The results of a pilot study in the Thukela Catchment indicated that modelling catchments at the quaternary catchment scale, *i.e.* South Africa has been divided into 1946 quaternary catchments which will be explained further in the sections to follow, was inadequate and subdivision of the quaternary catchments into sub-catchments and Hydrological Response Units (HRUs) was needed to produce realistic results. It was also found that area weighted soils and land cover information gave the best simulated runoff depths, compared to the observed runoff, in comparison to using the dominant soil and land cover information. Lastly, with respect to the spatial variability of rainfall, it was concluded that a greater representation of the spatial distribution of rainfall is needed (Chetty and Smithers, 2005; Smithers *et al.*, 2007).

More recently, Smithers *et al.* (2013) highlight and summarise several additional developments, undertaken by Smithers *et al.* (2007), to improve and refine the *ACRU* continuous simulation modelling approach to DFE. These additional developments are listed by Smithers *et al.* (2013) as follows:

(i) Firstly, a method to disaggregate daily rainfall into hourly totals in South Africa was developed and evaluated, in order to improve the shape of simulated hydrographs and the estimation of peak discharge. This was achieved using a regionalised semi-stochastic daily rainfall disaggregation model developed by Knoesen (2005). More details on the development, application and assessment of the method in South Africa are available from Knoesen and Smithers (2008) and Knoesen and Smithers (2009). The model, however, performed reasonably well with some suggestions to further refine certain aspects of the model (Smithers *et al.*, 2013).

(ii) Secondly, Frezghi (2005) assessed procedures developed by Pegram and Sinclair (2004) to merge rain-gauge and radar data using the Leibenbergsvlei Catchment in South Africa as a case study, due to the availability of detailed radar and gauged rainfall data for this catchment. The results indicated that the rain-gauges selected to represent the areal rainfall within sub-catchments, determined by merging point rainfall and radar rainfall measurements, generally over-estimated the mean areal merged rainfall values of the sub-catchments by considerable amounts. Frezghi (2005) therefore developed relationships between the merged rainfall fields for a catchment and rainfall data from specific rain-gauges, from the short period of available radar data, based on the premise that merged rainfall fields are the best available estimate of catchment rainfall. The relationship was subsequently used to adjust historical gauged daily rainfall data to better represent rainfall in the catchment (Smithers *et al.*, 2013).

(iii) Frezghi (2005) also assessed the stochastic, fine resolution space-time String-of-Beads Model (SBM) developed by Clothier and Pegram (2002) to simulate long series of rainfall over a catchment. This was done in order to more reliably estimate design floods. Observed statistics at a daily time scale were reproduced relatively well by the SBM, which were better than those at monthly or annual time scales. This was expected, due to the fact that the SBM is a short-duration rainfall model. The statistics of the selected rain-gauges used in the study were well reproduced spatially within the catchments. Frezghi (2005) concluded that the SBM may be used in rainfall-runoff modelling, including continuous simulation models, at detailed spatial and temporal scales, provided the SBM is appropriately calibrated (Smithers *et al.*, 2013).

(iv) Tewolde (2005) and Tewolde and Smithers (2006) developed and assessed techniques for flood routing in ungauged catchments using streamflow data from the Thukela Catchment. The results showed that the Muskingum-Cunge method may be used to route floods in ungauged catchments within the Thukela Catchment, with parameters estimated using empirical relationships (Smithers *et al.*, 2013).

The above mentioned refinements and developments to the *ACRU* modelling system were incorporated into the *ACRU* model by Smithers *et al.* (2007) and Smithers *et al.* (2013). Some notable findings of the study include the following (Smithers *et al.*, 2013):

(i) Errors in observed flow data, sparse rain-gauge networks and water abstractions, *i.e.* for irrigation, and water transfers between catchments made the application and verification of the *ACRU* continuous simulation model challenging.

(ii) The importance of extended historical rainfall records was highlighted, while the importance of accurate land cover information was also identified.

(iii) The need for detailed data on abstractions for irrigation and inter-catchment water transfers was also highlighted.

(iv) The observed flow data from the Department of Water and Sanitation (DWS) may not be consistent. Furthermore, the depth of flow recorded at gauging weirs frequently exceeds the rating table and therefore extension of rating tables is required. These points highlight the importance of only using quality controlled observed flow data to calibrate and verify continuous simulation models, and the danger of using poor observed data to calibrate models. Therefore, it is important to note that, in the study by Smithers *et al.* (2013), the model was not calibrated and physical catchment information was used and input into the model.

(v) In small catchments ($<150\text{km}^2$) simulated volumes and peak discharges were simulated well, while in larger catchments good simulations of flood volumes did not consistently translate into good simulations of peak discharges.

Ultimately, the results of Smithers *et al.* (2013) highlight the potential of the *ACRU* continuous simulation model to reproduce reliable and consistent estimates of design floods. Furthermore, Smithers *et al.* (2013) strongly recommend further development and verification of the CSM approach to DFE. Therefore, there is further scope and need for research into CSM and hydrological modelling in general.

From the sections reviewed on rainfall based methods for DFE, it has been highlighted that considerable effort has been expended in South Africa on both the SCS-SA and *ACRU* CSM approaches to DFE. In practice, the SCS-SA method is widely applied in small catchments in South Africa and reasonable estimates of design floods have been obtained from a frequency analysis of the hydrographs simulated using the *ACRU* model. There is therefore a clear link between the SCS-SA and *ACRU* models that needs further investigation, and instead of using a 30 day antecedent soil moisture budget, as is currently used to adjust for typically antecedent moisture conditions in the SCS-SA model, a continuous simulation of the soil moisture prior to all events may be simulated using the *ACRU* model. Smithers *et al.* (2013) recommended the refinement of the SCS-SA method utilising a CSM approach using the widely verified *ACRU* model and suggested that spatial discretisation could also be refined. The following chapter on hydrological modelling therefore focuses on the details and links between the SCS-SA and *ACRU* models.

3. HYDROLOGICAL MODELLING

In the previous chapter the potential of hydrological modelling for DFE was emphasised, including some of the benefits and shortfalls, with considerable attention focussed on the CSM approach advocated in the literature. In addition, it was highlighted that two hydrological models namely the SCS-SA and *ACRU* models, have received noticeable attention within South Africa. Furthermore, an important note was made regarding links between these two models. These links are investigated further in this chapter. One of the links between the models is that the median condition method of the SCS-SA model used the *ACRU* soil water budgeting procedure to adjust CNs based on the antecedent conditions calculated 30 days prior to the largest five annual rainfall events in each year of simulation, while the joint association method was developed using a frequency analysis of the simulated peak discharges. Secondly both the SCS-SA model and the *ACRU* model use the SCS (1956) runoff equation, as represented in Equation 3.1 (Schulze, 1995), to estimate stormflow:

$$Q = \frac{(P - cS)^2}{P + S(1 - c)} \tag{3.1}$$

where

Q = stormflow depth [mm],

P = gross daily precipitation amount [mm],

S = potential maximum retention [mm], or the soil water deficit, and

c = regression coefficient, commonly referred to as the coefficient of initial abstraction.

Therefore, one of the most striking similarities between both models is that they both use the same runoff equation, but with the SCS-SA method using Equation 3.1 for a single event, while the *ACRU* model uses Equation 3.1 to simulate continuous daily events. The manner in which the Soil Water Deficit (*S)* is computed, however, is considerably different in the models. The SCS-SA model uses a simplified approach, while the *ACRU* model disaggregates the soil water budget into its conceptual components in order to explicitly represent the processes that influence the soil moisture deficit prior to a rainfall event. These differences are highlighted in the sections to follow.

Prior to the analysis of each of the models, however, it is necessary to comment on the uncertainties inherent in all forms of hydrological modelling, including both the SCS-SA and *ACRU* models. Hughes *et al.* (2015) emphasise this reality, stating that it is essential for all role players involved in water resources management and assessment to understand the key concepts of uncertainty and to remember that virtually all of the information used to make decisions is uncertain. Hrachowitz *et al.* (2013) and Pomeroy *et al.* (2013) comment on the PUB decade, referring to the uncertainties involved in hydrological modelling. In their comments, they state that the aim of the PUB decade has been to reduce the uncertainties in hydrological modelling and parameter estimation through increased understanding of the complex processes and interactions associated with the hydrological cycle. Hughes (2013) cited in Pomeroy *et al.* (2013), reviewed implementing PUB within South Africa and comments on the historical reliance of most hydrological models on calibration from observed streamflow data and rainfall data, *i.e.* where the data is often patched (in-filled) to generate complete time series. According to Hughes (2013), current methods are still reliant on calibration to estimate model parameters, and these calibrated parameters are often subjectively transferred from gauged catchments to ungauged catchments based on catchment similarity. Hughes (2013) also highlights the inconsistency in parameter estimation across the country with different regions calibrating model parameters slightly differently, which adds to the uncertainties in hydrological modelling. Hughes (2013) therefore states that more communication between scientists and organisations is needed to collectively select and determine the most appropriate parameter values based on sound scientific knowledge and experience. These issues are extremely valuable to this study where links between the *ACRU* and SCS-SA model parameters are investigated. It is therefore important to note that these concerns and comments regarding parameter estimation and uncertainties have been noted within this study and that every effort has been made to ensure that parameter estimations and adjustments are based on acceptable scientific theory and realistic conceptualisation of hydrological processes.

3.1 SCS-SA Model

As alluded to in the previous chapters, extensive effort has been expended on refining and developing the SCS-SA model, for application in South Africa. The model, which has been verified and accepted as a suitable method to estimate design flood volumes and peak discharges for small catchments ($\leq$ 15km^2) in South Africa, is widely applied in practice (Schmidt and Schulze, 1987a; Schulze *et al.*, 2004; SANRAL, 2013). The SCS-SA and *ACRU* models use the same stormflow equation, as shown in Equation 3.1, but use different methods of determining *S*. The determination of *S* within the SCS-SA model is explained below.

As with the original SCS (1956) model, *S* in the SCS-SA model is dependent on the soil type, land cover, land management practice, hydrological condition and soil moisture status of the catchment (Schmidt and Schulze, 1987a). Theoretically the value of *S* can vary from zero to infinity, however, practical upper and lower limits of *S* have been defined as the permanent wilting point and porosity of the soil within a catchment. A catchment response index to rainfall, termed the runoff CN, was therefore introduced in order to transform the maximum soil water retention into a CN that varies within a more logical range of 0 to 100 (Schmidt and Schulze, 1987a). The derivation of CNs in South Africa was based on the determination of CNs by the Soil Conservation Service (SCS, 1972), with adaptations to South African conditions.

According to the original approach as detailed by Hawkins (1978), the CN values reported were calibrated from observations and estimated for different combinations of soils, land cover classes, land management practices and hydrological conditions. Soils as classified in the USA were divided into four hydrological soil groups, according to their infiltration rate and permeability, and termed Groups A, B, C and D. Soils that fall into Group A have the highest infiltration rate and permeability and therefore the lowest stormflow potential, while soils in Group D display the lowest infiltration rates and permeabilities and therefore the highest stormflow potentials (Hawkins, 1978). Based on the four hydrological soil groups, CNs were derived for different land cover classes, land management practices and hydrological conditions. This was achieved empirically by plotting daily rainfall and runoff for the annual maximum floods on graph paper for each of the aforementioned combinations. An "average" CN was selected for each scenario, *i.e.* a mean value representative of the plotted data. This data (obtained from research catchments located throughout the USA) was then used to derive median CNs for all of the catchments with the same combinations, *i.e.* of hydrological soil groups, land cover, land management practice and hydrological condition (Schmidt and Schulze, 1987a; USACE, 1994). Therefore, CNs derived for a catchment represent the "average" response coefficient for a range of independent events. The differences in CNs was generally attributed to differences in soil moisture (Schmidt and

Schulze, 1987a). Subsequently, using the spread of data from the rainfall-runoff plots, a methodology was included in the original SCS (1956) model to adjust average CNs (CN-II), for wet (AMC-III) or dry (AMC-I) antecedent moisture conditions which were related to the 5-day antecedent rainfall totals (Schmidt and Schulze, 1987a).

In the SCS-SA adaptation, the concept used to define soils into hydrological soil groups is slightly different and the number of soil groups was increased to seven in order to accommodate the wide range of soil types found in South Africa (Schmidt and Schulze, 1987a; Schulze, 2012). According to Schulze (2012), an expert group of soil and hydrological scientists used the South African Binomial Soil Classification (MacVicar *et al.*, 1977) to categorise the soils in South Africa into SCS soil groups. Based on the wide spectrum of properties found in South African soils, as well as the realisation that runoff is highly sensitive to soil properties, these experts added three intermediate soil groups to the original four groups resulting in the following seven hydrological soil groups: A, A/B, B, B/C, C, C/D and D. CNs for these soil groups, and similar land cover classes, management practices and hydrological conditions, as classified in the original SCS classification, were derived to produce a table of CNs for selected agricultural, suburban and urban land cover classes (Schmidt and Schulze, 1987a), an example of which is shown in Table 3.1.

Table 3.1 Initial CNs for selected land cover classes, land management practices and hydrological soil groups (after Schulze *et al*., 2004)

Land Cover Class	**Land Treatment/Practice/Description**	**Stormflow Potential**	**Hydrological Soil Group**						
			A	**A/B**	**B**	**B/C**	**C**	**C/D**	**D**
Fallow	1 = Straight row	-	77	82	86	89	91	93	94
	2 = Straight row + conservation tillage	High	75	80	84	87	89	91	92
	3 = Straight row + conservation tillage	Low	74	79	83	85	87	89	90
Row Crops	1 = Straight row	High	72	77	81	85	88	90	91
	2 = Straight row	Low	67	73	78	82	85	87	89
	3 = Straight row + conservation tillage	High	71	75	79	83	86	88	89
	4 = Straight row + conservation tillage	Low	64	70	75	79	82	84	85
	5 = Planted on contour	High	70	75	79	82	84	86	88
	6 = Planted on contour	Low	65	69	75	79	82	84	86
	7 = Planted on contour + conservation tillage	High	69	74	78	81	83	85	87
	8 = Planted on contour + conservation tillage	Low	64	70	74	78	80	82	84
	9 = Conservation structures	High	66	70	74	77	80	82	82
	10 = Conservation structures	Low	62	67	71	75	78	80	81
	11 = Conservation structures + conservation tillage	High	65	70	73	76	79	80	81
	12 = Conservation structures + conservation tillage	Low	61	66	70	73	76	78	79

Therefore, in terms of *S* in the SCS-SA model, as well as the original SCS model, the deficit is integrated into a single variable, *i.e.* the catchment CN. As mentioned, however, the CN may be adjusted to account for the antecedent moisture conditions. The median condition and joint association methods, which used the *ACRU* soil moisture budgeting routines to estimate the antecedent conditions 30 days prior to design rainfall events, was a major improvement to the original moisture adjustment procedure introduced into the original SCS (1956) model. However, the estimation of *S* and the resultant stormflow remains highly dependent on the CN selected.

The procedure used to assign a hydrological soil group to each of the soils listed in the Binomial Soil Classification is described as follows: Each of the 41 soil forms identified in the Binomial Classification were assigned to one of the seven groups, based on the overall stormflow related soil properties of the soil form (Schulze, 2012). The 41 soil forms are subdivided into soil series, of which 501 were identified and described by MacVicar *et al.* (1977), based on the physical and chemical properties of each soil series. The physical and chemical properties considered included texture, leaching, water table level and soil crusting. These properties were used to adjust each soil series, within a soil form, into a final hydrological soil group (Schmidt and Schulze, 1987a; Schulze, 2012). More recently, the Soil

Classification Working Group (SCWG, 1991) developed the Taxonomical Soil Classification system for South African soils. In this case the soils were divided into 73 soil forms, each identified by a sequence of diagnostic soil horizons. Each soil form was then further sub-divided into soil families on the basis of soil physical and chemical properties (Schulze *et al.*, 2004). Schulze *et al.* (1991) updated the hydrological soil groups for the soil forms and series for the Binomial Soil Classification and the soil forms and families for the Taxonomic Soil Classification and the results were tabulated, and included in Schulze *et al.* (1992), Schulze *et al.* (2004) and the *ACRU* User Manual (Smithers and Schulze, 2004). Therefore, where soils information is available, *i.e.* in terms of soil form and family or form and series, the assigned SCS-SA soil response group is available. Alternatively, based on field analysis of the soils within the catchment under investigation, the hydrological soil group may be selected based on the characteristics of the four basic SCS hydrological soil groups, as classified by the SCS (1972), according to their infiltration rate and permeability (Schulze *et al.*, 2004). Schmidt and Schulze (1987a) suggest that further adjustment of soils information may be performed after field based observations using the following characteristics; soil depth, surface sealing, topographic position and parent material. Schulze *et al.* (2004), however, emphasises that runoff estimated by the SCS-SA equation is highly sensitive to the hydrological soil group selected, and therefore care should be taken when selecting the appropriate group.

3.2 *ACRU* Model

The daily time-step *ACRU* agrohydrological model (Schulze, 1995) is a physical conceptual model. The model is conceptual since it is made up of idealised concepts, and physically based as physical processes are explicitly represented (Schulze *et al.*, 1994). Therefore, ultimately *ACRU* is not a parameter fitting or optimising model (Schulze *et al.*, 1994). The model is designed to represent the actual physical characteristics of a catchment as estimated or obtained in the field. However, detailed information is often not available and therefore continuous work and development at the University of Natal/KwaZulu-Natal has been undertaken over a long period of time by several staff members and postgraduate students to develop a national database of default input information needed by the model, *e.g.* climate data, soils and land cover information (Smithers and Schulze, 2004). Simultaneously, continual refinement to the *ACRU* modelling system has also been undertaken, in terms of how processes are conceptualised, as continuous research adds to the understanding of complex hydrological processes and their interactions (Smithers and Schulze, 2004).

South Africa has been divided into primary, secondary and tertiary catchments based on drainage basins and topography. Based on these delineations, databases of information such as those mentioned above have been developed and updated for use in hydrological models, such as the *ACRU* model, which can be used to support decisions for the management of water resources. However, these delineations were found to be too coarse and therefore the tertiary catchments were divided into 1946 quaternary catchments, each assigned with default input parameters required by the *ACRU* model. These model inputs are stored in what is called the quaternary catchments database (Schulze, 2013). More recently, each quaternary catchment has been further sub-divided into three sub-catchments based on natural breaks in altitude, resulting in 5837 quinary catchments, with default model input values once again being assigned to several of the input variables required by the model, and stored in the Quinary Catchments Database (QCD) (Schulze, 2013). This refinement in the catchment discretisation was done because several studies, including, *inter alia*, Smithers *et al.* (2007) and Smithers *et al.* (2013), have shown that the model performs better on smaller catchments, with Smithers and Schulze (2004) stating that catchments should ideally be modeled at a catchment scale less than $50km^2$. Schulze (2013) states that in the Quaternary and Quinary Catchments Databases each individual quaternary and quinary has been assigned a unique climate file with 50 years of daily rainfall values (derived from Lynch, 2003), maximum and minimum temperatures (derived from Schulze and Maharaj, 2004), solar radiation (derived from Schulze and Chapman, 2008a), reference potential evaporation by the Penman-Monteith technique (Penman, 1948; Monteith, 1981; with values derived from Schulze and Chapman, 2008b) and relative humidity (derived from Schulze, 2008), as well as hydrological soil attributes (derived from Schulze and Horan, 2008) and hydrological attributes of baseline land cover represented by the Acocks (1988) Veld Types (derived from Schulze, 2004). Thus the land cover information in the Quaternary and Quinary Catchments Databases have been assigned default values representative of natural land cover and not current/actual land cover information which is necessary to accurately estimate design flood volumes and peaks with the *ACRU* model, as highlighted by Smithers *et al.* (2013). Clark (2014) is developing a standardised land cover/land use hierarchical classification system and classes that will accommodate the classifications used in updated land cover databases, these are elaborated on in the recommendations chapter of this document. An additional benefit of using a continuous simulation model, such as the *ACRU* model, for DFE is that anticipated future land use/land cover changes may be input into the model to estimate design flows for current as well as future land use/land cover conditions (Smithers *et al.*, 2013). The various components of the hydrological cycle, as conceptualised within the *ACRU* model, are depicted in Figure 3.1.

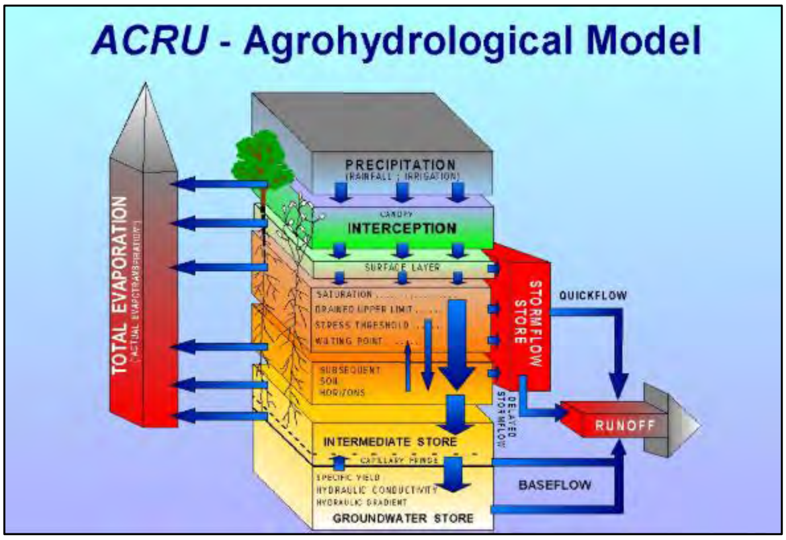


Figure 3.1 Conceptualised hydrological components and processes as structured in the *ACRU* model (Schulze, 1995)

Referring to Equation 3.1 and Figure 3.1, it is evident that the major driving input into the *ACRU* model is precipitation (P). The surface runoff component, *i.e.* stormflow (Q) simulated in the *ACRU* model, is produced from excess precipitation, *i.e.* the total rainfall minus the amount of rainfall initially abstracted, is a function of the magnitude of the rainfall and S in the critical response depth of the soil (Smithers and Schulze, 2004). The topsoil and subsoil soil moisture deficit is continuously simulated on a daily basis in the model. This is therefore a major improvement on the median condition and joint association techniques used in the SCS-SA model. In the *ACRU* model, however, conceptual and practical refinements to the SCS runoff equation used in the SCS-SA model were performed (Schulze, 1995). These include the following (Schulze, 1995):

(i) Interception is abstracted separately and before the commencement of potential stormflow producing rainfall. Therefore, it is not part of the initial abstractions as assumed in the SCS and SCS-SA model.

(ii) The coefficient of initial abstraction may be altered month-by-month in the *ACRU* model, dependent on the characteristics of the vegetation and site, as well as the land management practices. In addition, the soils information used in the *ACRU* model is far more detailed than that used in the SCS-SA model.

(iii) *S*, conceived as a Soil Water Deficit, is calculated by the multi-layer soil water budgeting techniques of *ACRU*, avoiding the need for the determination of a final catchment CN. *S* is calculated as the difference between water retention at porosity and the actual soil water content prior to a rainfall event, after the total evaporation for the day has been abstracted. The soil water budgeting procedures will be elaborated on further in the paragraphs to follow, after analysis of the surface runoff component, *i.e.* Stormflow (*Q*), is completed.

(iv) *S* is calculated for a selected Critical Response Depth of the Soil (*SMDDEP*). *SMDDEP* is dependent on, *inter alia*, the climate, vegetation and soil properties, *i.e.* MAP and rainfall intensity, vegetation density linked to rainfall and MAP and dystrophic, mesotrophic or eutrophic soils (Smithers and Schulze, 2004). The runoff generated is therefore strongly influenced by the *SMDDEP* and the moisture content of the soil prior to a rainfall event.

(v) In addition, the daily release of *Q* is controlled by a Quick Flow Response Coefficient (*QFRESP*) which partitions the Stormflow (*STORMF*) generated from a rainfall event, *i.e. Q* in Equation 3.1, into a Same Day Response Fraction (*UQFLOW*) and a subsequent delayed stormflow response which is added to the next days' stormflow, which is again partitioned based on the *QFRESP* coefficient.

The residual rainfall, that is abstracted and is not intercepted and does not contribute to stormflow, *i.e.* the surface runoff component, infiltrates into the topsoil (A horizon) and replenishes the soil water store via the following processes (Smithers and Schulze, 2004):

(i) Once the topsoil reaches full capacity, *i.e.* field capacity, "excess" water percolates into the subsoil (B horizon) as saturated drainage, *i.e.* the soil structure within the *ACRU* model is divided into an A (topsoil) and B (subsoil) horizon, an intermediate zone and a groundwater store (Figure 3.1).

(ii) The rate of drainage from the A horizon into the B horizon is dependent on the respective soil characteristics such as texture, porosity and wetness.

(iii) Once the subsoil becomes saturated, water continues to percolate further down the soil profile, into the intermediate zone and eventually into a groundwater store which contributes to runoff as baseflow (Figure 3.1). Baseflow is modeled explicitly in the *ACRU* model.

(iv) Unsaturated water distribution both up and down the soil profile also occurs, however, at a much slower rate than under saturated conditions.

These processes therefore add water to the soil horizons and groundwater store and directly influence *S*. Another important hydrological process which also has a major influence on *S* is total evaporation (Figure 3.1). Total evaporation encompasses evaporation from previously intercepted water, soil water evaporation, *i.e.* from the topsoil only, and plant transpiration from all horizons in the root zone (Smithers and Schulze, 2004). Reference Potential Evaporation (E_r) is used with other soil and plant properties to estimate the Actual Total Evaporation (*E*). These soil and plant properties include the soil moisture status, the type of vegetation, the vegetation cover factor, the root depth and the plant growth stage (Smithers and Schulze, 2004). The soil moisture status is required to calculate the actual total evaporation as it regulates the evaporation rate from the soil and the transpiration rate of plants. Therefore, parameters such as the Porosity (PO), Permanent Wilting Point (PWP), Drained Upper Limit (DUL), Plant Available Water (PAW), Critical Soil Water Content (ψ), Crop Coefficients (*CAY*) and a Coefficient of Initial Abstraction (*COIAM*) have been defined for soils and plants, in order to determine the point at which the actual total evaporation drops below the Maximum Total Evaporation (E_m) of a specific soil and plant combination (Smithers and Schulze, 2004). These soil properties, as well as others, have been mapped for the country using the Land Type maps (SIRI, 1987) developed and published by the Soil and Irrigation Research Institute (SIRI), now the Agricultural Research Council's Institute for Soil, Climate and Water (ARC-ISCW) (Schulze, 2012). This was performed using a computer programme called AUTOSOILS, developed by Pike and Schulze (1995) and revised by Schulze and Horan (2005), which translates information from the Land Type databases into soils information needed by the *ACRU* model (Schulze, 2012). Vegetation properties for five land cover categories, namely urban land uses, agricultural crops, natural vegetation, aquatic systems and commercial forests, as classified by Schulze and Hohls (1993) and depicted in Figure 3.2, have also been developed and incorporated into a database called COMPOVEG, which is built into the *ACRU* model (Smithers and Schulze, 2004).

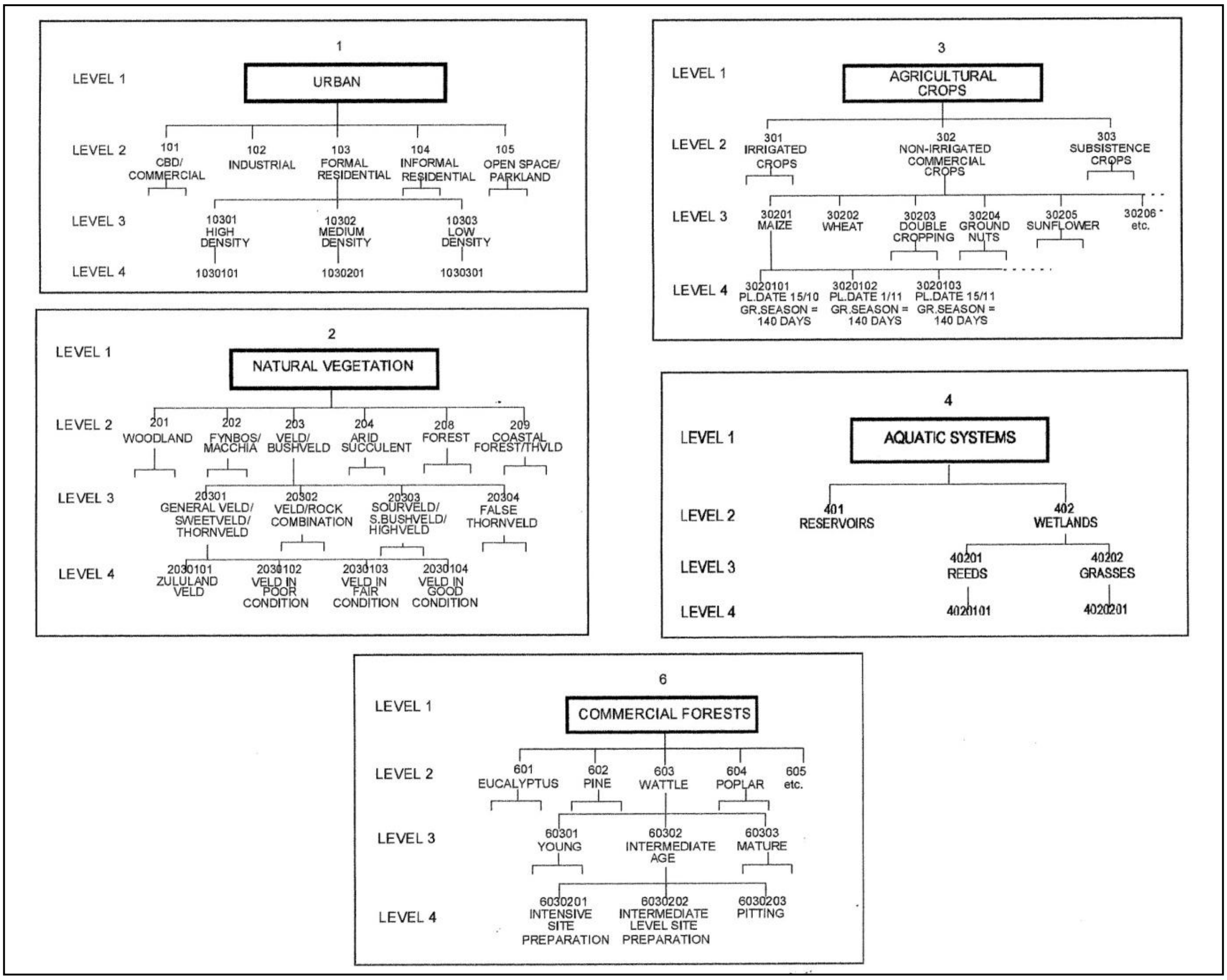


Figure 3.2 The four-level structure of the land cover/land use classification developed for the *ACRU* model (Schulze, 1995)

The COMPOVEG database contains land cover specific *ACRU* variables, at differing levels of detail, which is continually updated as new research findings are obtained. As stated above, however, the Acocks (1988) natural land cover map is currently the only national land cover map readily available, for which *ACRU* variables have been assigned. In addition, the land cover classification developed by Schulze and Hohls (1993) does not account for land management practice and hydrological condition. For example from Figure 3.2, an agricultural crop such as maize is represented by a single general class, accounting only for different planting dates, based on the location where the maize is to be cultivated. Therefore in the *ACRU* land cover classification no account is taken of land management practice, as accounted for in the SCS-SA land cover classification (Table 3.1), and hydrological condition is not adequately and consistently represented in the *ACRU* classification. In terms of the latter, hydrological condition is represented by classes such as subsistence and commercial crops for a select few crops. Natural vegetation is also inconsistently represented in terms of hydrological condition, *e.g.* in the *ACRU* classification there are several different grassland/veld species such as those represented in the Acocks (1988) natural land cover classification, however, only a single general set of classes for veld in poor, fair and good condition have been classified, *i.e.* instead of a poor, fair and good class for each grassland/veld species within the classification. Forestry, however, is represented in far greater detail in *ACRU* due to the extensive research conducted on forest plantations and their impacts on water resources. Degradation has more recently been accounted for in the *ACRU* classification for each of the Acocks (1988) natural land cover classes. This degradation, however, is not to be confused with hydrological condition and is representative of land degradation specifically by overgrazing and erosion.

As mentioned above, Clark (2014) is developing a standardised land cover/land use hierarchical classification system that includes classes such as the aforementioned degradation classes. This classification aims to improve on and update the classification of Schulze and Hohls (1993) and includes the current state of the art information derived from continuous research and the expert knowledge of Schulze (2013). The Clark (2014) classification still does not account for land management practice and does not adequately account for hydrological condition, as it is accounted for in the SCS-SA model. The hierarchical classification of Clark (2014), however, is adaptable and has been set-up to easily accommodate the addition of new classes as they are developed. More details on the mapping of soils is available from Schulze (2012) and more details on the current *ACRU* land cover classification, developed by Schulze and Hohls (1993), and the new hierarchical classification, currently being developed, are available from Schulze (1995) and Clark (2014) respectively.

The estimation of peak discharge is another important component which both the SCS-SA and *ACRU* models compute. Both the SCS-SA and *ACRU* models use the same peak discharge equation, once again adopted from the original SCS model (SCS, 1972).

The original SCS peak discharge equation is based on the triangular unit hydrograph concept, as detailed by Schmidt and Schulze (1987) and is expressed mathematically as follows:

$$\Delta q_p = 0.2083 \left(\frac{A \Delta Q}{\frac{\Delta D}{2} + L} \right) \tag{3.2}$$

where

Δq_p = peak discharge of an incremental triangular hydrograph [$m^3.s^{-1}$],

A = catchment area [km^2],

ΔQ = incremental runoff depth [mm],

ΔD = incremental duration of effective rainfall [hours], and

L = catchment lag [hours].

The effective storm duration and particularly catchment lag have traditionally been some of the most difficult parameters to estimate or determine when calculating peak discharge. Therefore, in the SCS-SA as well as the *ACRU* model, four options are available to estimate catchment lag, namely (i) the T_c; (ii) the addition of travel times along flow reaches; (iii) the original SCS lag equation; and (iv) the Schmidt-Schulze lag equation. Catchment lag time is dependent on several properties such as the soil characteristics, catchment size, slope and rainfall intensity. More details on these equations may be obtained from, *inter alia*, Schmidt and Schulze (1984); Schmidt and Schulze (1987a); Schulze *et al.* (1992) and Schulze (1995). The simulation of peak discharge was not investigated in this study because the focus was on obtaining similar trends in runoff volumes. Investigation of runoff volumes however, is an important and critical first step needed. It is clear from Equation 3.2 that accurate estimates of design runoff volumes (Q) are essential to obtaining accurate estimates of peak discharge, along with the calculation of catchment lag. Gericke (2011) has initiated research into the estimation of catchment response time (lag), identifying that contradictory definitions of catchment response time are found in the literature and therefore has proposed the development of a single method that can be universally applied within South Africa to determine catchment response time. Therefore, the calculation of peak discharge is an additional component that needs further examination leading on from the preliminary investigations and results from this study.

Having reviewed the SCS-SA and *ACRU* models and providing the necessary background required to understand the methodology proposed, the following section will elaborate on the general methodology adopted in this study.

4. GENERAL METHODOLOGY

This chapter contains a brief outline of the general methodology that was applied in this study. In Chapter 3, the links and similarities between the SCS-SA and *ACRU* models were identified. Furthermore, as highlighted in Section 3.1 on the SCS-SA model, the land cover classification accounts for differences in runoff responses that result from differences in land management practices and hydrological conditions. This is not accounted for in the current *ACRU* land use/land cover classification, nor in the classification being developed by Clark (2014).

The CNs used in the original SCS model were derived from observations, and the SCS-SA model is an accepted method of DFE in small catchments in South Africa (Schmidt and Schulze, 1987a; Schulze *et al.*, 2004; SANRAL, 2013). Thus, it was assumed in this study that the design volumes simulated by the SCS-SA are reasonable, and that the relative changes in design volumes simulated by the SCS-SA model as a consequence of changes in land management practices or condition are also reasonable. Thus, the general approach to the study is to investigate how design volumes simulated by the SCS-SA model for various land management practices or conditions can be simulated by the *ACRU* model, and to derive classes in the *ACRU* hierarchical classification for land management practice and hydrological condition based on the SCS-SA classification. Therefore, design runoff volumes and changes in design runoff volumes, for different management practices and hydrological conditions, as simulated by the SCS-SA model, will be used as a substitute for observed data, *i.e.* as a reference, to achieve similar design runoff volumes and changes in design volumes in the *ACRU* model. This is achieved by adjusting relevant variables in the *ACRU* model to represent the change in management practice or condition, as represented in the SCS-SA model. It is important to note that, as a starting point, the current state of the art information derived from continuous research and the expert knowledge of Schulze (2013) was used as the initial input into the *ACRU* model and adjustments were made from these expert opinions on how to simulate management practices in the *ACRU* model.

To achieve the above, the first step taken was to investigate the correlation between the soil representation in the SCS-SA and *ACRU* models, recalling from the previous chapters that (i) in the SCS-SA model soils are integrated into a single runoff response index, *i.e.* the CN which accounts for the land cover, land management practice and antecedent soil moisture; and (ii) in the *ACRU* model soils are represented explicitly and in detail, with the land cover and management conditions being modelled by varying the input soils and land cover variables which control the various hydrological process, *e.g.* interception of rainfall by vegetation, vegetation crop coefficients and the initial abstraction of rainfall to account for impacts of surface conditions on infiltration.

The following chapters focus on the different approaches that were investigated to achieve this goal. The results revealed that correlation of SCS-SA soil groups to *ACRU* soil textural properties alone is not adequate. This lead onto a sensitivity analysis of *ACRU* input variables related to soil properties, as well as land cover information, to identify which *ACRU* input variables are most sensitive in terms of design runoff volumes. The sensitivity analysis was then used to refine the initial approach and a correlation between SCS-SA CNs and specific *ACRU* variables was investigated. The methodology and results of each of the steps mentioned above are presented in the following chapters so as to group the information together in a structured and accessible manner. The following chapter therefore addresses the initial attempts made to correlate SCS-SA soils to *ACRU* soils.

5. SCS-SA TO *ACRU* SOIL TRANSLATION

As highlighted in the previous chapters, the land cover classification used in the SCS-SA model (Schulze *et al.*, 2004), an example of which was shown in Table 3.1, accounts for different land management practices and hydrological conditions, which are not accounted for in the current *ACRU* land cover classification, nor in the standardised hierarchical classification system being developed by Clark (2014). In the *ACRU* hierarchical classification, for example, a common row crop such as maize is represented by a single general class, *i.e.* "Agriculture Commercial Maize Dryland Summer Rainfall Region". Therefore as a starting point, a decision was made to use the SCS-SA land cover classes to derive equivalent classes in the hierarchical classification for use in *ACRU*. By way of example, Table 3.1 contains information for a row crop land cover class in the SCS-SA classification and indicates that there are several subclasses based on different land management practices and hydrological conditions, *i.e.* straight or contoured rows, conservation practices, and conservation structures. Hydrological condition is represented by stormflow potential, *i.e.* high stormflow potential is representative of poor hydrological condition.

The general approach proposed to derive similar subclasses in the *ACRU* land cover hierarchical classification was as follows: (i) assign the general class classification, *e.g.* Agriculture Commercial Maize Dryland Summer Rainfall Region, to the most representative subclass in the SCS-SA classification, *e.g.* Row crop, planted on contour, low stormflow potential/good hydrological condition; (ii) use the representative changes in runoff from the SCS-SA model going from the selected subclass to another subclass to derive similar subclasses in the *ACRU* hierarchical classification, *i.e.* by adjusting relevant *ACRU* input variables for the general class in order to obtain similar changes in runoff volumes to those simulated by the SCS-SA model. In the SCS-SA classification, however, the hydrological response from each subclass varies according to hydrological soil groups A – D (Table 3.1). In order to compare the impact of management practices and cover conditions simulated by the models, it was necessary to try to have the two models simulating the same soil characteristics, *e.g.* for an A soil in the SCS-SA model it was necessary to determine the equivalent *ACRU* input parameters required to represent a SCS-SA A soil group in *ACRU*.

In order to translate SCS-SA soils information into *ACRU* soils input information, it is necessary to review and emphasise the differences in soils input variables between the SCS-SA and *ACRU* models. As noted in Chapter 3.1, the SCS-SA soils information is represented by the catchment CN for hydrological soil groups A – D. In the *ACRU* model, however, soils are characterised by soil retention parameters (Schulze, 1995). *S* in *ACRU* is calculated as the difference between water retention at porosity and the actual soil water content just prior to a rainfall event. Therefore, in the *ACRU* model soil retention properties and response factors are required as input into the model and include soil depth, PWP, DUL, PO and soil texture dependent redistribution rates for water fluxes between the A and B horizon of the soil (Schulze, 1995).

Two soil input options are available in *ACRU* based on the information available. Option (i) is selected when inadequate soils information is available and the user inputs only a soil textural class and default soil depth ranges. Soil water retention constants, redistribution rates and other information required by the model are pre-programmed into *ACRU* for each soil textural class (Schulze, 1995). Option (ii) is selected when adequate soils information such as retention constants are available, *i.e.* either from laboratory or field analysis of the soil or from databases such as the Land Type database where soil depth, PWP, DUL, PO and redistribution rates have been derived per Land Type using a computer programme called AUTOSOILS developed by Pike and Schulze (1995) and revised by Schulze and Horan (2005). More details on the above mentioned Land Types are given in the succeeding section.

The objective of the soil translation, therefore, is to identify *ACRU* soil input values to represent each of the SCS-SA soil groups that will produce similar hydrological responses to those obtained for the SCS-SA model. By way of example, Figure 5.1 illustrates the trends in runoff volume calculated by the SCS-SA model for a Veld land cover, in fair hydrological condition, and shows the increasing runoff trend from an A to D soil in the SCS-SA model for different return period events. The design rainfall used is also depicted in Figure 5.1. The aim is to use these trends as a guide as to which *ACRU* variables may be used, to represent A to D soils in *ACRU* in order to achieve similar runoff responses for a similar veld/grassland land cover in the *ACRU* hierarchical classification.

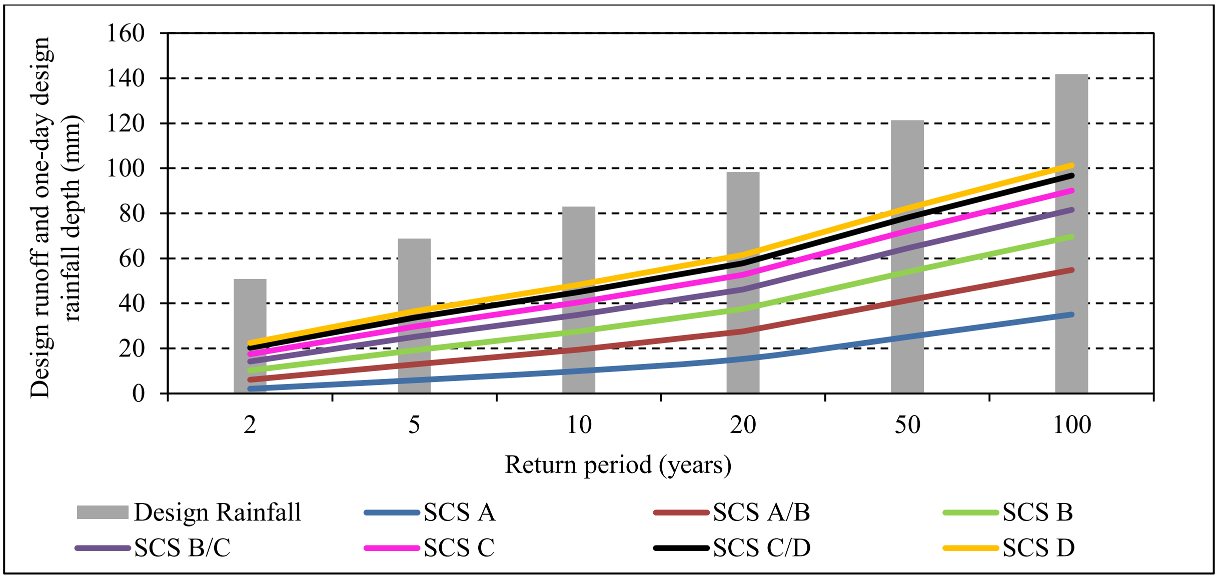


Figure 5.1 SCS-SA hydrological responses computed for a veld land cover, in fair hydrological condition, for soil groups A – D at specific return periods and the input design rainfall

In order to isolate the simulation of changes in management practices and cover conditions from soil characteristics, it is necessary to ensure equivalence of soils information input to the models. The following sections describe three initial attempts made to achieve this *ACRU* to SCS-SA soil translation. In each section, some background to each approach is given, followed by the methodology and results.

5.1 The Land Type Approach

The first step taken to achieve this translation was to review the literature and identify previous efforts made to relate SCS-SA soils to *ACRU* soil inputs. The review highlighted some recent work documented by Schulze (2012), where hydrological soil groups were mapped over South Africa for use with the SCS-SA model. Realising the importance of soil response groups and the difficulty in assigning hydrological response groups to a catchment, Schulze (2012) identified a need to map SCS-SA soil response groups, *i.e.* groups A, A/B, B, B/C, C, C/D, D, for South Africa. This would enable more rapid determination of these response groups when using the SCS-SA model to determine stormflow responses for any catchment in South Africa. This was seen to be beneficial as obtaining soils information is often challenging and if information is to be obtained from field work, the process is costly and time consuming.

To achieve this, the following steps were undertaken (Schulze, 2012):

(i) Selection of the most detailed soil map for South Africa for which inventories/databases were available.
(ii) Selection of a quantitative metric (a numerical description of soil properties) already mapped for the most detailed soils map available.
(iii) Translate/link the quantitative metric to the SCS-SA soil groups.
(iv) Map SCS-SA soil groups and analyse the results.

The most detailed soils maps available for South Africa were the Land Type maps developed and published by the former Soil and Irrigation Research Institute (SIRI, 1987), now the ARC-ISCW. The Land Type maps define or group classes of land based on macroclimate, terrain form and soil pattern uniformity (Schulze, 2012). The classification of Land Types, however, was based more on agricultural rather than hydrological soil properties. Ultimately, the Land Type maps were generated by superimposing detailed climate maps for a specific region over pedosystem maps. Each classified Land Type is accompanied by inventories/databases collected from terrain, soil and climate data analysed for each Land Type. These databases contain a range of information including the percentage coverage of each Land Type by individual soil series, particularly relevant to determining SCS-SA soil response groups, and the soil physical properties of each soil series making up the Land Type. It is important to note that the soils described in the Land Type maps are based on the Binomial Soil Classification, and for consistency, the Binomial Soil Classification remains as the classification system used in all detailed soils maps across South Africa (Schulze, 2012). Hence, the Binomial Soil Classification was used by Schulze (2012) when mapping SCS-SA hydrological soil groups. The mapped hydrological response of a Land Type is based on the area weighted average of the responses of the individual soil series it is made up of, or contains. The Land Types of South Africa were classed into nine broad groups based on soil patterns, *i.e.* Groups A – I. Each group was then further subdivided into map units, coded Aa, Ab, Ac, *etc*., with the mapping unit representing, for example, soils uniform in colour, base status and depth range. Approximately 22 000 polygons of Land Types are defined for South Africa (Schulze, 2012).

The next step involved identifying a quantitative metric, already mapped at the resolution of the Land Type maps, which would be representative of the hydrological response of soils, *i.e.* in terms of soil infiltration rates and permeability rates. This quantitative metric needed to reflect properties such as soil texture and changes in texture, *i.e.* clay content, with depth down the soil profile, such that it is representative of water movement and distribution through the soil and hence represents the stormflow potential of a soil. The metric used was the Soil Water Content (ϴ) of a soil at PWP (Schulze, 2012). The PWP of the soil was found to be dependent on soil texture and specifically the clay content and distribution of clay down the soil profile. Based on these findings, Schulze (2012) details how the PWP values were mapped for South Africa, originating from a major conceptual breakthrough by Schulze *et al.* (1985) who identified five vertical clay distribution models for South Africa. For each vertical clay distribution model, clay classes (a – e) representing different percentages of clay content were categorised. Each soil series identified in the South African Binomial Classification was then assigned a vertical clay distribution model and class based on the description and definition of each soil series (Schulze, 2012). Equations developed by Hutson (1984) and Schulze *et al.* (1985) were then used to calculate typical values of soil water content at the PWP and the DUL for each clay distribution model and class. The AUTOSOILS computer programme developed by Pike and Schulze (1995) and revised by Schulze and Horan (2005), was used to translate information from the Land Type databases into maps of PWP for the A and B horizon, across South Africa, at the spatial resolution of the Land Types, *i.e.* the 22 000 polygons. This mapping was not limited to PWP and DUL values and included other soil properties required by the *ACRU* model such as A and B horizon soil depths, porosities and drainage rate factors.

In addition, the quantitative metric, *i.e.* the soil water content at PWP, was linked to SCS-SA soil groups. This was performed by finding relationships between the SCS-SA soil groups, clay distribution models and classes, and soil water contents. Using these relationships and assigning weighting values to each of the SCS-SA soil groups, *i.e.* A = 1 to D = 7, weighted SCS-SA soil group values were determined for each clay distribution model and class. Using this information, SCS-SA soil weightings were assigned to water content values at PWP for the A and B horizon, as shown in Table 5.1. Full details on this mapping are contained in Schulze (2012).

Table 5.1 Assigned SCS-SA soil weightings and final SCS-SA soil groups (after Schulze, 2012)

Soil Water Content at PWP for the A horizon: Θ_{PWPA} (m.m^{-1})	**Soil Water Content at PWP for the B horizon: Θ_{PWPB} (m.m^{-1})**	**Weight**	**SCS-SA Soil Group**
< 0.075		Weight 1 = 1.5	
	< 0.075	Weight 2 = 1.5	A
	0.075 - 0.090	Weight 2 = 2.3	A/B
	0.090 - 0.120	Weight 2 = 6.0	B/C
	> 0.120	Weight 2 = 3.1	A/B
0.075 - 0.105		Weight 1 = 2.5	
		Weight 2 = 2.5	A/B
0.105 - 0.120		Weight 1 = 3.0	
		Weight 2 = 3.0	B
0.120 - 0.155		Weight 1 = 5.3	
		Weight 2 = 5.3	C
0.155 - 0.190		Weight 1 = 4.0	
		Weight 2 = 4.0	B/C
0.190 - 0.220		Weight 1 = 6.1	
	< 0.165 (#5d)*	Weight 2 = 5.0	C/D
	0.165 - 0.220 (#2d)	Weight 2 = 6.1	C/D
	> 0.220 (#3k)	Weight 2 = 7.0	D
> 0.220		Weight 1 = 4.8	
	< 0.255 (#2e)	Weight 2 = 6.1	C
	> 0.255 (#1e)	Weight 2 = 4.0	B/C

*(#5d): Clay distribution model 5d, and so forth for #2d, #3k, #2e and #1e.

The averaged SCS-SA soil group weighting, *i.e.* for the topsoil and subsoil was then used with defined weighting ranges, assigned by Schulze (2012), to determine the final SCS-SA soil group (last column Table 5.1). Using this information, SCS-SA soil groups were mapped for South Africa at the spatial resolution of the Land Type Polygons, as depicted in Figure 5.2.

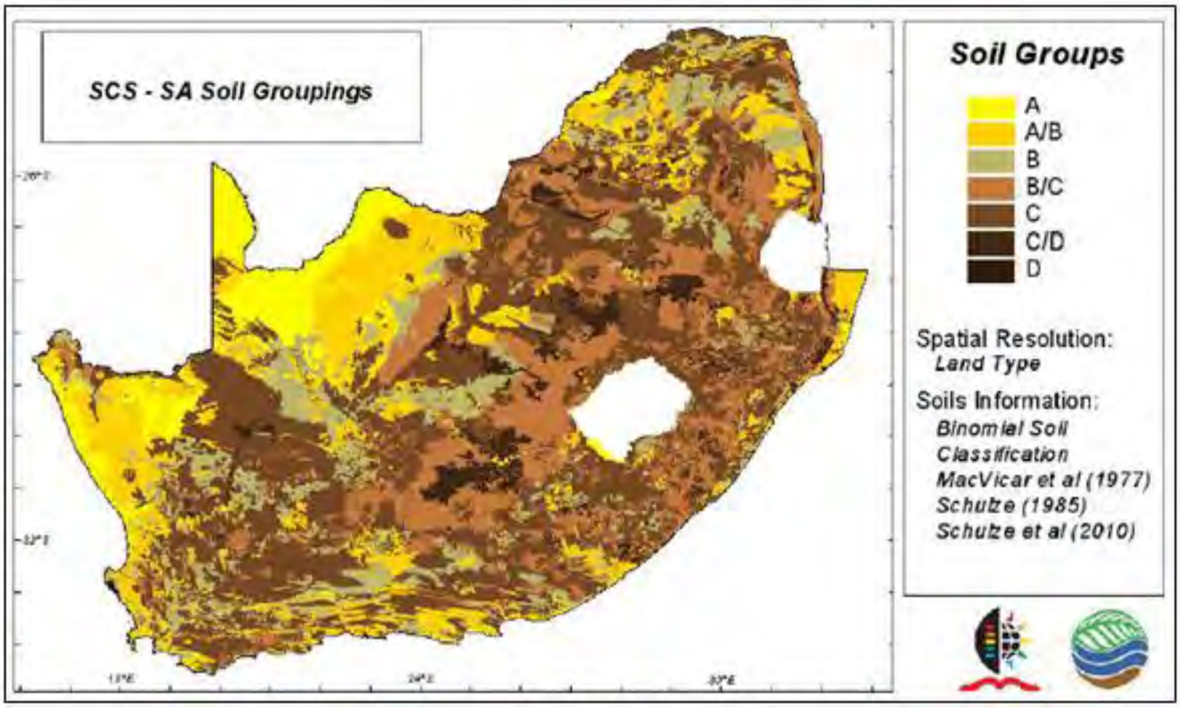


Figure 5.2 SCS-SA soil groups A to D as distributed over South Africa (Schulze, 2012)

In terms of the requirements for this study, it is evident that the results summarised in Table 5.1 are unsuitable. The reason being that in certain cases a SCS-SA soil group has more than one set of PWP values, *e.g.* from Table 5.1 an A/B soil can have a topsoil PWP water content (Θ_{PWPA}) < 0.075 with two possible ranges of subsoil PWP water contents (Θ_{PWPB} 0.075 – 0.090 and Θ_{PWPB} > 0.120), as well as a Θ_{PWPA} value within the range 0.075 – 0.105. This makes assigning a SCS-SA soil group to a unique range of PWP values not possible. Therefore, the results are unsuitable since the objective is to derive a single set of *ACRU* soil input parameters that represent each individual SCS-SA hydrological soil group. The findings of Schulze (2012), however, did provide initiative for further analysis of the data and results from the study, to identify general trends that would be useful in representing SCS-SA soil groups in *ACRU*. The methodology applied to identify general trends is described below.

5.1.1 Methodology

In order to further investigate the SCS-SA soil groups derived by Schulze (2012) per Land Type, the original Excel spreadsheet with area weighted values of PWP, DUL, PO, soil depths, soil response factors and SCS-SA soil groups for each of the Land Type polygons was obtained. This data was sorted by assigned SCS-SA soil groups A – C/D which revealed that no SCS-SA D group soils were derived by Schulze (2012) for any of the Land Types. Consultation with Schulze (2015), however, explained that this is because D soils generally make up such small percentages of the Land Types and therefore, after area weighting the soils, the possibility of getting a D soil at the Land Type scale is non-existent. The results of the analysis are presented in the following section.

5.1.2 Soil translation results

After sorting the Land Type data by assigned SCS-SA soil groups, simple statistics were performed on the data and Box and Whisker diagrams were plotted for each of the derived SCS-SA soil groups, as depicted in Figure 5.3. In Figure 5.3, the abbreviation A_B is the default fraction of water above the DUL of the A horizon that is redistributed into the B horizon of the soil on a daily basis in the *ACRU* model. It should be noted that the Box and Whisker plots depicted in Figure 5.3 were calculated for the topsoil, based on the premise that the effective (critical) depth of the soil from which stormflow generation takes place is generally defaulted to the depth of the A horizon in *ACRU*. Very similar trends to that of the topsoil, however, were found for the subsoil when plotting Box and Whisker diagrams for the subsoil.

From Figure 5.3 a few general trends are evident. Before analysing and addressing these trends, however, it is necessary to comment on the Box plot data for SCS-SA soil group A. From the results (Figure 5.3) it is seen that the minimum and 25th percentile values, for all the variables investigated, are both zero. Zero values for these properties, however, are not possible. A likely reason for the zero values is due to an error in the AUTOSOILS computer programme. When assigning PO, DUL, PWP, PAW and A_B values for each Land Type water bodies were assigned zero values, in order to identify these areas as water bodies. Consequently, since Schulze (2012) used the PWP ranges in Table 5.1 to assign each Land Type to a SCS-SA soil group, the zero values fell within the range for SCS-SA soil group A, *i.e.* $\Theta_{PWPA} < 0.075$ and $\Theta_{PWPB} < 0.075$. Consequently, this resulted in the zero values for water bodies now being classified as SCS-SA A soil groups, and possibly explains the anomalous trend in the Box and Whisker plots for SCS-SA soil group A. This, however, requires further investigation and is recommended in future research. Regardless of the anomalous trend identified for SCS-SA soil group A, several general trends are clear.

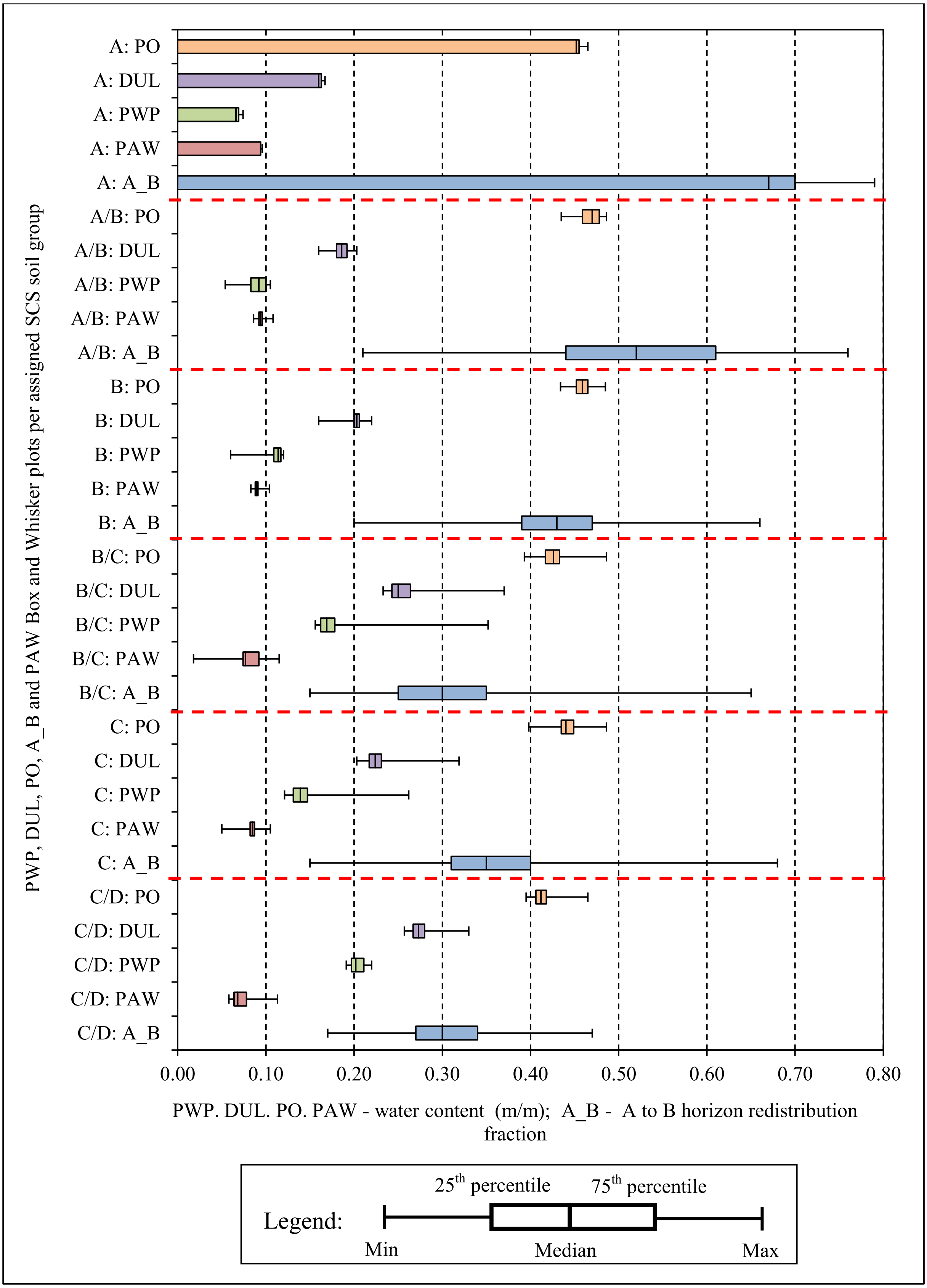


Figure 5.3 Box and Whisker plots of Land Type data for each assigned SCS-SA topsoil group

Firstly, for the median PWP and DUL values there is an increasing trend in the median values from the assigned SCS-SA A soils to B/C soils. The trend then reverses going from assigned SCS-SA B/C soils to C soils where the median values for assigned SCS-SA C soils is lower than the median for SCS-SA B/C soils. The trend then reverses once again back to an increase in the median values going from assigned SCS-SA C soils to C/D soils. Therefore, it is evident from the results that the assigned SCS-SA C soils are not consistent with the general trend of increasing median PWP and DUL values going from SCS-SA soil groups A to C/D. Furthermore, the assigned SCS-SA C soils continue to be inconsistent to the general trends for values of PO, A_B response and PAW. For example, considering the median PO values going from assigned SCS-SA A soils to C/D soils, there is a slight increase in PO from assigned SCS-SA A soils to A/B soils, followed by a decreasing trend in PO from assigned SCS-SA A/B soils to C/D soils, except for assigned SCS-SA C soils where the trend is not followed and the PO increases. Similarly, in terms of A_B response there is a decreasing trend evident from assigned SCS-SA A soils to C/D soils except, once again, for assigned SCS-SA C soils where an increase in A_B response is observed. Finally, in terms of PAW there are slight differences noticeable with a decreasing trend in the median values, except for assigned SCS-SA C soils where the median PAW content increases slightly.

5.1.3 Simulation results

From the results contained in Figure 5.3 for the topsoil, it is evident that using the derived information, *e.g.* the median values of PWP, DUL, PO, A_B and PAW obtained for each SCS-SA soil group, to simulate design runoff volumes in the *ACRU* model will likely produce inconsistent runoff trends. To confirm this, the median values of PWP, DUL, PO, A_B and PAW obtained for the topsoil and subsoil from each of the assigned SCS-SA soil groups, *i.e.* as shown for the topsoil in Figure 5.3, were used in *ACRU* as the soils input information to represent each SCS-SA soil group. In addition, the other *ACRU* model input variables and data, such as land cover and rainfall, were input to be equivalent to the inputs to the SCS-SA model used to obtain the results depicted in Figure 5.1. The objective of this analysis is to assess if the results simulated by the *ACRU* model show similar absolute as well as relative trends to those from the SCS-SA model (Figure 5.1). A veld land cover, in fair hydrological condition, was used in the SCS-SA model simulation to obtain the results shown in Figure 5.1. Therefore, a similar veld land cover [Crop Number – 2030322 – The Southern Tall

Grassveld (Acocks #65)] was selected from the COMPOVEG database built into the *ACRU* model (Smithers and Schulze, 2004) for the *ACRU* simulations. The land use/land cover information used in the *ACRU* model is based on the current state of the art information derived from continuous research and the expert knowledge of Schulze (2013). It is important to note that in this assessment, a hypothetical catchment area of 1km^2 was used in both the SCS-SA and *ACRU* model simulations for comparison, assuming climatic and physical catchment conditions for a randomly selected quinary catchment near Bergville in KwaZulu-Natal (KZN), Quinary V11L3 (Quinary number – 4854, in the QCD), depicted in Figure 5.4. Quinary V11L3 near Bergville was initially selected due to the fact that this area is a large maize producing region within KZN. Maize is an important agricultural crop cultivated in South Africa and was consequently identified as an important land cover class to investigate within this study. Therefore Quinary V11L3 near Bergville was selected as a representative area for investigation within KZN.

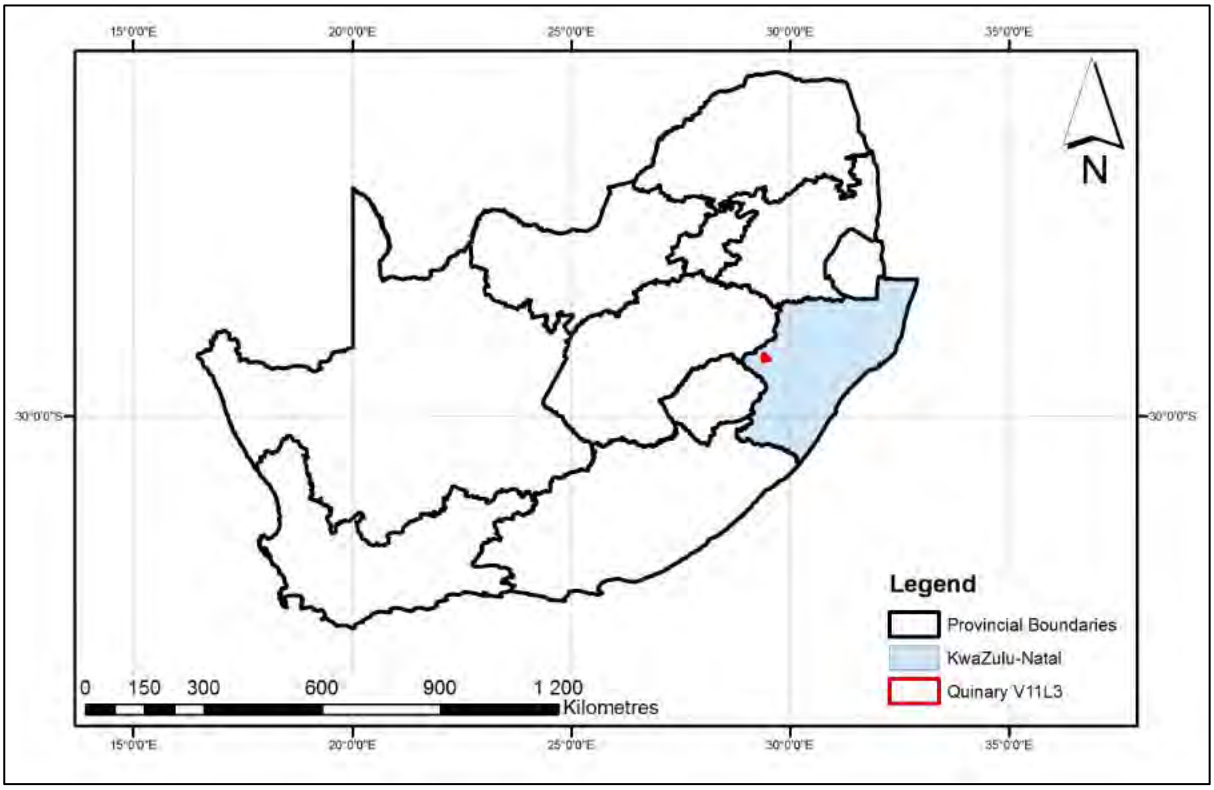


Figure 5.4 Location map of Quinary V11L3 (MAP – 716mm) in KZN, South Africa

The daily rainfall file assigned to Quinary 4854 was used as the input into the *ACRU* model and the same daily rainfall file was used to calculate the design rainfall input values for the SCS-SA model. The design rainfall values were determined using the *ACRU* Time Series

Analysis software to calculate the LP-III extreme value distribution for the input daily rainfall file from Quinary 4854. The design runoff volumes in the SCS-SA model are calculated for these input design rainfall values, *i.e.* the return period of each design runoff event is equal to the return period of the design rainfall used. In the *ACRU* simulations, a frequency analysis of the daily runoff volumes is used to estimate the design runoff volumes. Consequently the return period of a design runoff event in *ACRU* may not be the same as the return period of the causative rainfall, owing to dependence on the soil moisture status, *i.e.* the antecedent soil moisture conditions are explicitly accounted for on a daily basis within the *ACRU* soil moisture budgeting routines. The soil depths were matched in both the SCS-SA model and *ACRU* model. In addition, since the SCS-SA model conceptualises that all runoff occurs on the same day of the rainfall event, *QFRESP* was set to one in *ACRU* so that all surface runoff generated in the *ACRU* model from a rainfall event would leave the catchment on the same day as the rainfall event. The results from the *ACRU* runs are shown in Figure 5.5.

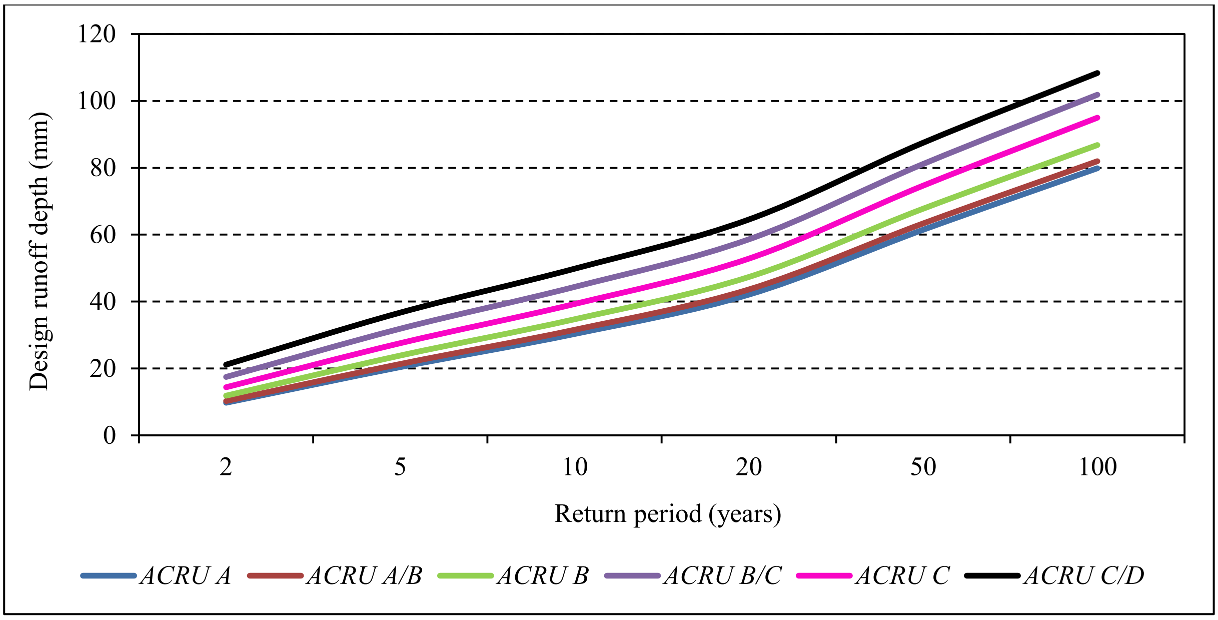


Figure 5.5 *ACRU* hydrological responses computed for a veld land cover, in fair hydrological condition for SCS-SA assigned soil groups A – C/D at specific return periods, Land Type approach

In Figure 5.5, *ACRU A* to *ACRU C/D* represents the runoff computed in *ACRU* for the inputs derived to represent the assigned SCS-SA soil classes. Figure 5.5 shows that the inconsistencies identified from Figure 5.3 are directly translated into the runoff volumes simulated by the *ACRU* model, where the runoff from an *ACRU C* soil diverges from the general trend of increasing runoff from an equivalent *ACRU A* to *C/D* soil. The decrease in runoff observed for an *ACRU C* soil can be explained by referring back to Figure 5.3 and the trends identified. To describe why this decrease in runoff occurs for an *ACRU C* soil requires re-analysis of how *S* is calculated in the *ACRU* model. *S* is determined for the critical soil depth, *i.e.* defaulted to the A horizon in *ACRU*, and is calculated as the difference between the soil water content at PO and that held by the soil column prior to the rainfall event (Schulze, 1995). Therefore, in terms of runoff generation, the PO and PWP of the soil are important parameters since they define the limits of the maximum storage capacity of the soil. The PO being the upper limit or maximum soil water content the soil may achieve, and the PWP being the lower limit or minimum soil water content the soil may achieve. Based on this logic and recalling the following general trends from Figure 5.3: (i) there is a decreasing trend in PO values but the PO increased for assigned SCS-SA C soils, and (ii) there is an increasing trend in PWP values but the PWP decreased for assigned SCS-SA C soils. Thus, the general trend from assigned SCS-SA A to C/D soils is a decrease in the maximum storage capacity of the soil, but for assigned SCS-SA C soils the storage capacity increases. Consequently less runoff is generated from the assigned SCS-SA C soils in *ACRU* (*ACRU C* soils) compared to the assigned SCS-SA B/C soils in *ACRU* (*ACRU B/C* soils), since the *ACRU C* soil has a greater maximum soil water storage capacity. In addition, going from assigned SCS-SA B/C soils to C soils the A_B response fraction increases, which is again in contrast to the general trend, and therefore is an additional factor resulting in the decrease in simulated runoff going from an *ACRU B/C* to *C* soil. This is because a greater fraction of water above the DUL of the soil drains from the A horizon of an *ACRU C* soil resulting in a larger soil water deficit and consequently less runoff. In addition, comparison of the absolute runoff volumes from the SCS-SA simulations (Figure 5.1) with those from the *ACRU* simulations (Figure 5.5) reveal that there are considerable differences in the runoff volumes simulated, with a general over simulation of the absolute runoff volumes by the *ACRU* model relative to the volumes simulated by the SCS-SA model. Figure 5.6 reinforces this observation graphically, where the results from Figure 5.1 and Figure 5.5 have been plotted together on the same set of axes.

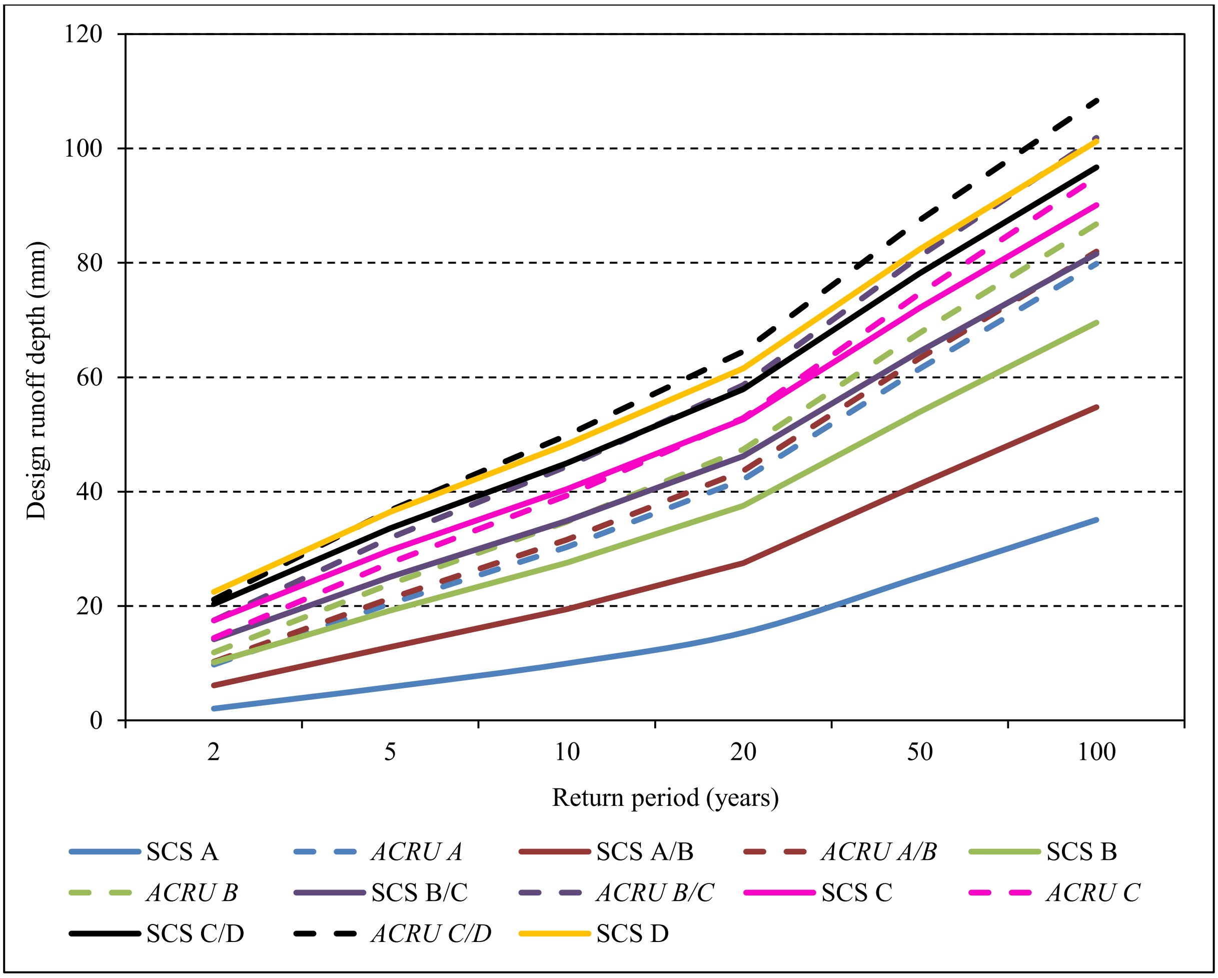


Figure 5.6 SCS-SA and *ACRU* Land Type soil runoff simulations plotted on the same set of axes for a veld land cover, in fair hydrological condition at specific return periods

In the SCS-SA simulations, for example, there is a greater range in the runoff volumes from an A soil to a C/D soil, with the runoff volumes being considerably lower, especially for the A to B/C soils, compared to those obtained from the *ACRU* simulations (Figure 5.6). Figure 5.7 depicts the average absolute differences between SCS-SA and *ACRU* design runoff volumes (averaged for all return periods from 2 – 100 years) for each SCS-SA soil group A to D, for the Land Type approach. Figure 5.7 concisely summarises and quantifies the differences between the *ACRU* and SCS-SA simulation results, which is easier to analyse and interpret for comparison to the other methods which follow. The results are presented as absolute differences since various attempts to represent the results as percentage differences yielded inaccurate and misleading results. The main reason for this is due to the fact that the number ranges for the various return periods as well as soil groups are not consistent. For example, the design runoff volumes increase going from the 2 year return period to the 100 year return period, as well as simultaneously generally increasing from SCS-SA soil group A (low runoff producing soils) to SCS-SA soil group D (high runoff producing soils). For this reason at the lower return periods the values are smaller numbers and therefore small absolute differences are large percentage differences and vice versa for higher return periods. The same case is true when comparing the design runoff volumes for low runoff producing soils with those from high runoff producing soils. Therefore when representing the results as percentage differences, the results are strongly skewed and become misleading and difficult to interpret and compare. The absolute differences on the other hand are absolute and show the actual differences. It is noted that the absolute differences generally do not show the significance of the changes, however, in this analysis it is important to make accurate and meaningful comparisons between the simulation results, as that is the objective of the study, which is believed to be best achieved by presenting the results as absolute differences.

In order to quantify the significance of the absolute differences between the SCS-SA and *ACRU* simulation results, the following general rules were developed:

(i) Highly comparable: the average absolute change ≤ 2mm.

(ii) Comparable: 2mm < average absolute change ≤ 6mm.

(iii) Poorly comparable: 6mm < average absolute change ≤ 10mm.

(iv) Incomparable: the average absolute change > 10mm.

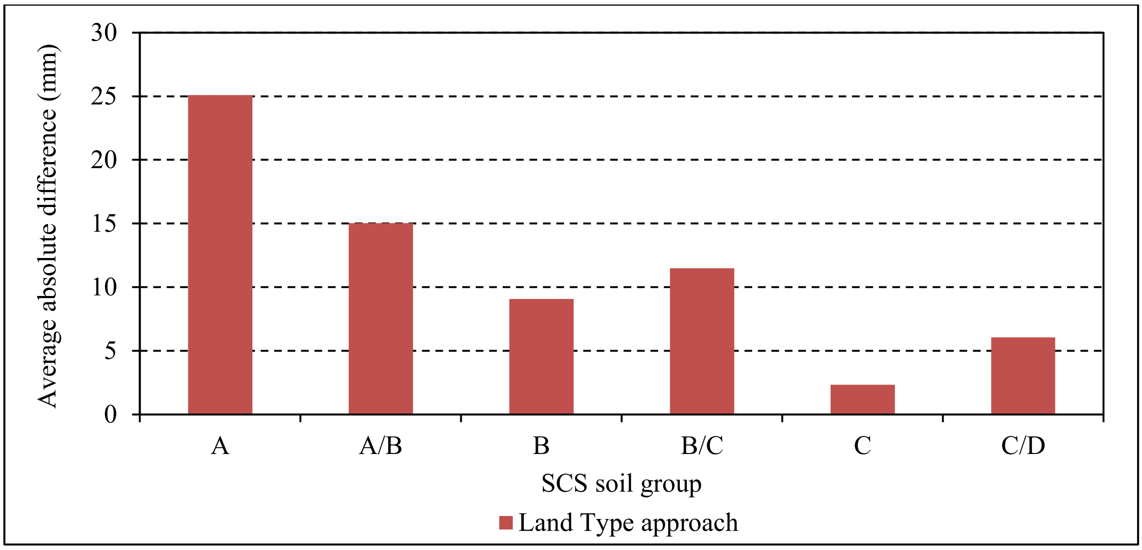


Figure 5.7 Average absolute difference between SCS-SA and *ACRU* design runoff simulations (averaged for all return periods from 2 – 100 years) for the Land Type approach

Figure 5.7 quantitatively reinforces the observation that the differences in runoff volumes between SCS-SA soil groups A – C/D are noticeably different, with a general over simulation of the absolute runoff volumes by the *ACRU* model relative to the volumes simulated by the SCS-SA model, especially for SCS-SA soil groups A to B/C. The greatest difference is observed for SCS-SA soil group A with an average absolute difference of 25mm. In terms of the general rules outlined previously, the results are comparable for SCS-SA soil group C only; incomparable for SCS-SA soil groups A, A/B and B/C; and poorly comparable for SCS-SA soil groups B and C/D.

An additional important comparison that needs to be investigated between the SCS-SA and *ACRU* simulation results, in line with the objectives of the study, is to compare the runoff trends between the two models. This was investigated by comparing the average ratio change (averaged for all return periods from 2 – 100 years) going from SCS-SA soil group A to each of the subsequent soil groups A/B to D in both the SCS-SA and *ACRU* models, as depicted in Figure 5.8. The results presented in Figure 5.8 show that there is an increasing trend in the average ratio change going from SCS-SA soil group A/B to D for the SCS-SA simulation results. This trend is also seen for the *ACRU* simulation results, with the exception once again of SCS-SA soil group C for the reasons identified previously with regard to the soil properties assigned to SCS-SA soil group C in *ACRU* by the Land Type approach. The quantitative ratio changes from the *ACRU* simulations, however, are considerably lower compared to the SCS-SA ratio changes. Therefore in terms of the runoff trends obtained from the Land Type approach in the *ACRU* model, the differences in runoff responses between SCS-SA soil groups A - D are poorly represented in comparison to the SCS-SA model.

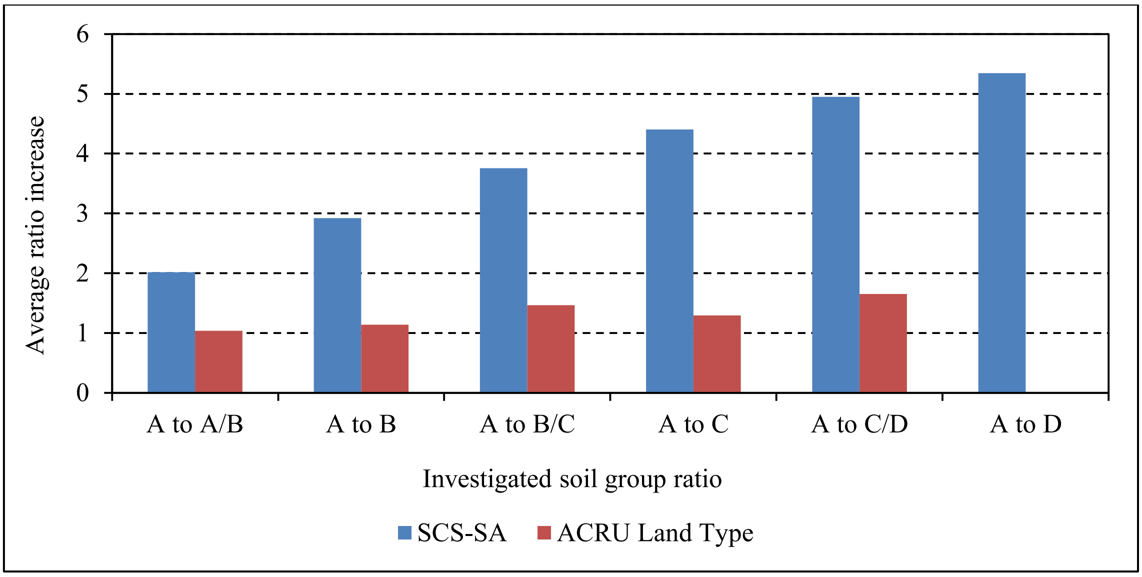


Figure 5.8 Average ratio change in design runoff depths calculated for each SCS-SA soil group (A/B to D) relative to SCS-SA soil group A for both the SCS-SA and *ACRU* simulation results (averaged for all return periods from 2 – 100 years), Land Type approach

Ultimately the inconsistencies identified suggest that the analysis of SCS-SA soil groups assigned using the Land Type data, undertaken by Schulze (2012), to derive *ACRU* soil inputs corresponding to SCS-SA soil groups was unsuccessful. Consequently a second investigation was undertaken to translate the SCS-SA soils information into *ACRU* soils information, as explained in the following section.

5.2 The Binomial Soil Classification Approach

The second investigation to convert SCS-SA soils into equivalent *ACRU* soils was a simpler one and involved a review of the Binomial Soil Classification (MacVicar *et al.*, 1977) and the texture classes assigned to SCS-SA soil groups, as reported by Smithers and Schulze (2004). This is based on the theory that runoff response in the SCS-SA model is dependent on soil infiltration and permeability rates, which are in turn strongly influenced by soil texture, therefore a relationship between assigned SCS-SA soil groups and texture classes may be obtained. The following methodology was therefore applied.

5.2.1 Methodology

The soils in the Binomial Soil Classification, an example of which is shown in Table 5.2, were arranged by SCS-SA soil groups and the percentage of each soil texture class that made-up a SCS-SA soil group was tabulated (Table 5.3).

Table 5.2 Binomial Soil Classification example (after Smithers and Schulze, 2004)

LEGEND					
c	crusting	Sa	sand	0	no/low interflow potential
l	leaching	Cl	clay	X	some interflow potential
t	texture	Lm	loam	XX	high interflow potential
w	water table				

Soil Form	Code	Soil Series	SCS Grouping	SCS Adjustment Factor	Clay Distribution Model	Typical Texture Class	Interflow Potential	Erosion Hazard Rating
ARCADIA	Ar 10	Mngazi	C/D		2e	Cl	0	Low
C/D	Ar 11	Bloukrans	C/D		2e	Cl	0	High
	Ar 12	Noukloof	C/D		2e	Cl	0	Low
	Ar 20	Gelykvlakte	C/D		2e	Cl	0	Mod
	Ar 21	Clerkness	C/D		2e	Cl	0	High
	Ar 22	Zwaarkrygen	C/D		2e	Cl	0	Mod
	Ar 30	Rydalvale	C/D		2e	Cl	0	Low
	Ar 31	Rooidraai	C/D		2e	Cl	0	Low
	Ar 32	Nagana	C/D		2e	Cl	0	Low
	Ar 40	Arcadia	C/D		2e	Cl	0	Mod
	Ar 41	Eenzaam	C/D		2e	Cl	0	Mod
	Ar 42	Wanstead	C/D		2e	Cl	0	Mod
AVALON	Av 10	Mastaba	A	+l/+t	1a	LmSa	X	High
B	Av 11	Welverdiend	A	+l/+t	1a	LmSa	X	High
	Av 12	Banchory	A	+l/+t	1a	Sa	X	High
	Av 13	Ashton	A/B	+l	1b	SaLm	X	High
	Av 14	Kanhym	A/B	+l	1b	SaLm	X	High
	Av 15	Wolweberg	A	+l\+t	1b	SaLm	X	High

Table 5.3 SCS-SA soil groups and texture class percentages

A Soils	No. (%)	A/B Soils	No. (%)	B Soils	No. (%)	B/C Soils	No. (%)	C Soils	No. (%)	C/D Soils	No. (%)	D Soils	No. (%)
SaLm	33.3	SaLm	31.5	SaLm	38.0	SaLm	29.2	SaClLm	49.2	SaCl	41.4	Cl	14.3
LmSa	30.9	LmSa	26.9	LmSa	16.3	SaCl	25.0	SaLm	23.0	Cl	20.7	LmSa	10.7
Sa	13.6	Sa	9.3	SaClLm	15.2	SaClLm	20.8	SaCl	9.8	SaClLm	17.2	LmSa/SaClLm	10.7
SaClLm	9.9	SaClLm	8.3	SaCl	12.0	LmSa	12.5	Cl	8.2	LmSa/SaClLm	5.2	SaClLm	10.7
LmSa/SaClLm	3.7	Cl	5.6	Sa	6.5	Sa	8.3	LmSa	6.6	SaClLm/SaCl	5.2	SaLm	10.7
SaLm/SaClLm	3.7	LmSa/SaClLm	5.6	Cl	5.4	Cl	4.2	Sa	1.6	LmSa/SaLm	3.4	SaCl	8.9
Cl	2.5	SaCl	5.6	LmSa/SaClLm	2.2			Sa/SaLm	1.6	SaLm/SaClLm	3.4	LmSa/SaLm	7.1
SaCl	2.4	SaLm/SaClLm	2.8	Lm/SaclLm	1.1					LmSa	1.8	SaLm/SaClLm	7.1
		ClLm	1.8	Sa/SaClLm	1.1					Sa/SaClLm	1.7	SaCl/Cl	5.4
		SLm/SClLm	1.8	SaCl/SaClLm	1.1							Sa	3.6
		CLm/SaClLm	0.8	SaLm/SaClLm	1.1							Sa/SaClLm	3.6
												Sa/SaLm	3.6
												SaClLm/SaCl	3.6

Furthermore, in the *ACRU* Theory Manual (Schulze, 1995) and *ACRU* User Manual (Smithers and Schulze, 2004), default soil water retention values, A and B horizon response fractions and saturated hydraulic conductivities (Ks) have been assigned to soil texture classes as input to the model when only texture class is known (Table 5.4). Thus, for each texture class, as summarised in Table 5.3, default soil input information required by the *ACRU* model is available. Initial analysis of Table 5.3 indicated that it was not possible to select a single soil texture class to represent each SCS-SA soil group as: (i) each SCS-SA soil group has a range of possible texture classes, and (ii) even if an attempt was made to assign the most common (modal) texture class found within a SCS-SA soil group to that group, SCS-SA soil groups A to B/C would all be represented by a Sandy Loam (SaLm) texture class. Therefore, the soil water retention values and response fractions for each SCS-SA soil group were derived by using the distribution of texture percentages in Table 5.3 as weights, along with the soil water retention values and response fractions for the textural classes listed in Table 5.4.

Table 5.4 Default soil water retention values, response fractions and saturated hydraulic conductivities pre-programmed into *ACRU* (after Schulze, 1995; Smithers and Schulze, 2004)

Texture Class Number	Texture Class	PWP ($m.m^{-1}$)	DUL ($m.m^{-1}$)	PO ($m.m^{-1}$)	ABRESP/ BFRESP*	Ks (mm/h)
1	Clay	0.298	0.416	0.482	0.150	0.600
2	Loam	0.128	0.251	0.464	0.500	13.000
3	Sand	0.050	0.112	0.430	0.800	210.000
4	Loamy Sand	0.068	0.143	0.432	0.700	61.000
5	Sandy Loam	0.093	0.189	0.448	0.650	26.000
6	Silty Loam	0.121	0.272	0.495	0.450	6.800
7	Sandy Clay Loam	0.159	0.254	0.402	0.500	4.300
8	Clay Loam	0.195	0.312	0.468	0.400	2.300
9	Silty Clay Loam	0.190	0.335	0.473	0.350	1.500
10	Sandy Clay	0.228	0.323	0.423	0.400	1.200
11	Silty Clay	0.253	0.390	0.480	0.250	0.900

*ABRESP: Fraction of soil water above DUL that drains from the A horizon into the B horizon of a soil; BFRESP: Fraction of soil water above DUL that drains from the B horizon of the soil into the intermediate groundwater zone; Ks: Saturated hydraulic conductivity of the soil.

5.2.2 Soil translation results

Using the above method, the percentage weighted PWP, DUL, PO and ABRESP/BFRESP values tabulated in Table 5.5 were calculated to represent each SCS-SA soil group in *ACRU*.

Table 5.5 Percentage weighted soil water retention values and response fractions

Parameter	A Soils	A/B Soils	B Soils	B/C Soils	C Soils	C/D Soils	D Soils
PWP ($m.m^{-1}$)	0.096	0.112	0.126	0.142	0.153	0.209	0.153
DUL ($m.m^{-1}$)	0.181	0.200	0.217	0.233	0.248	0.308	0.246
PO ($m.m^{-1}$)	0.434	0.436	0.434	0.430	0.424	0.431	0.435
ABRESP/BFRESP	0.648	0.610	0.582	0.554	0.518	0.403	0.517

With reference to the PWP and DUL in Table 5.5, there is a general increasing trend from a SCS-SA A soil to D soil, except for a SCS-SA D soil where the PWP and DUL decreases to similar values found for a SCS-SA C soil. It is also noteworthy that the increase in PWP and DUL values going from a SCS-SA C soil to C/D soil is far greater than the increases observed between SCS-SA soils A to C. A similar trend is seen for the ABRESP/BFRESP fraction showing a decreasing trend from a SCS-SA A soil to D soil, except for a SCS-SA D soil where the ABRESP/BFRESP fraction increases to a similar value found for a SCS-SA C soil. The ABRESP/BFRESP fraction change is also far greater going from a SCS-SA C soil to C/D soil compared to the differences between SCS-SA soils A to C. No clear pattern is seen with respect to the PO values. The values fluctuate up and down slightly but generally the values are very similar with no major changes between SCS-SA soil groups. Through analysis of the results and recollection of the trends observed from the previous investigation to derive *ACRU* soil inputs to represent SCS-SA soil groups, it is evident that runoff results will reflect a decrease in runoff for a SCS-SA D soil in comparison to a SCS-SA C/D soil in *ACRU*. This is due to an increase in the maximum soil water storage capacity (PO – PWP), as well as the ABRESP/BFRESP fraction, going from SCS-SA soil group C/D to SCS-SA soil group D, which is inconsistent with the general trend.

5.2.3 Simulation results

To assess the impact of the above conversion, the soils information from Table 5.5 representing SCS-SA soil groups, were input into *ACRU* using the same configuration detailed in Section 5.1.3, with the results depicted in Figure 5.9.

The results shown in Figure 5.9 confirm the observations made above showing a general increase in runoff, however, with a decrease in runoff observed for an *ACRU D* soil using the soil input information listed in Table 5.5. Consequently, when comparing the trends from Figure 5.9 and Figure 5.1, there is still a discrepancy between the outputs. In the SCS-SA simulations runoff continues to increase from a SCS-SA A to D soil, whereas in the *ACRU* simulations the same general trend is followed with the exception of an *ACRU D* soil where the runoff decreases to below that of an *ACRU C* soil. In addition, once again the absolute runoff volumes from the *ACRU* simulations (Figure 5.9) are not similar to those of the SCS-SA simulations (Figure 5.1).

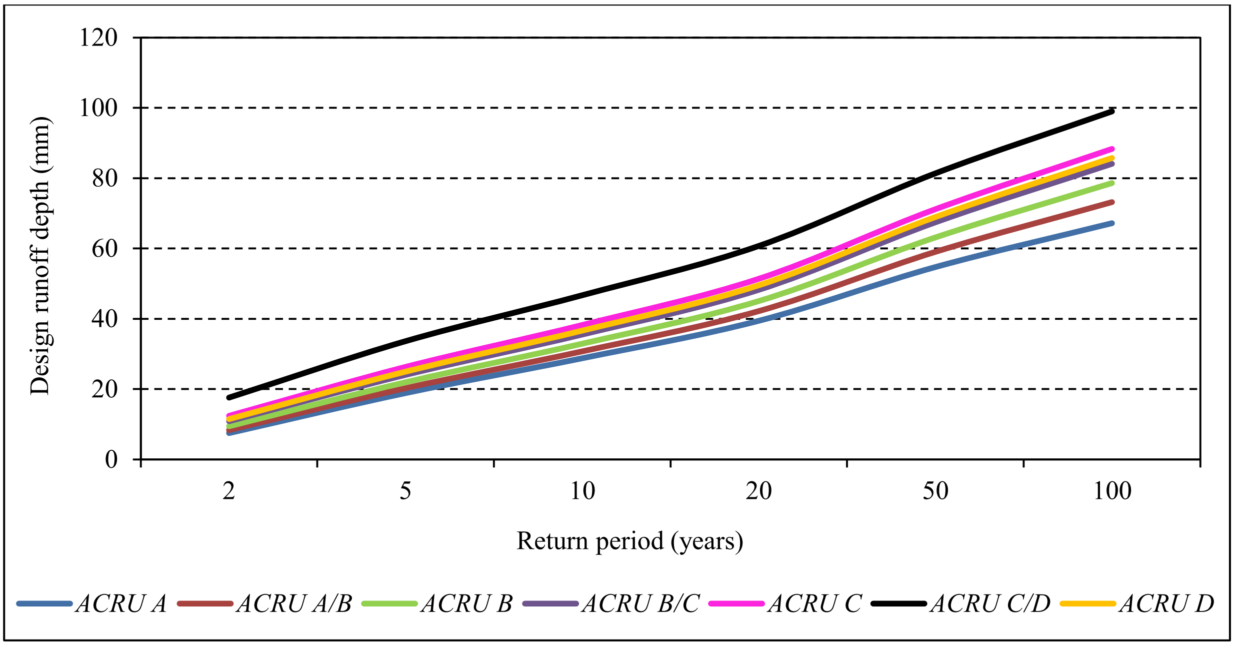


Figure 5.9 *ACRU* hydrological responses computed for a veld land cover, in fair hydrological condition for SCS-SA assigned soil groups A – D at specific return periods, Binomial approach

The results, however, are promising and are an improvement on the results from the Land Type approach, as highlighted in Figure 5.10. Figure 5.10 depicts the average absolute differences between SCS-SA and *ACRU* design runoff volumes (averaged for all return periods from 2 – 100 years) for each SCS-SA soil group A to D, for both the Land Type and Binomial approaches. The results show that the average percentage difference between SCS-SA and *ACRU* design runoff volumes are consistently lower for the Binomial approach, indicating greater similarity between the SCS-SA and *ACRU* runoff simulations under the Binomial approach. There are, however, still considerable differences between the *ACRU* and SCS-SA simulation results for SCS-SA soil groups A, A/B and D, where the results are incomparable. Comparable results, however, were obtained for SCS-SA soil groups B, B/C, C and C/D.

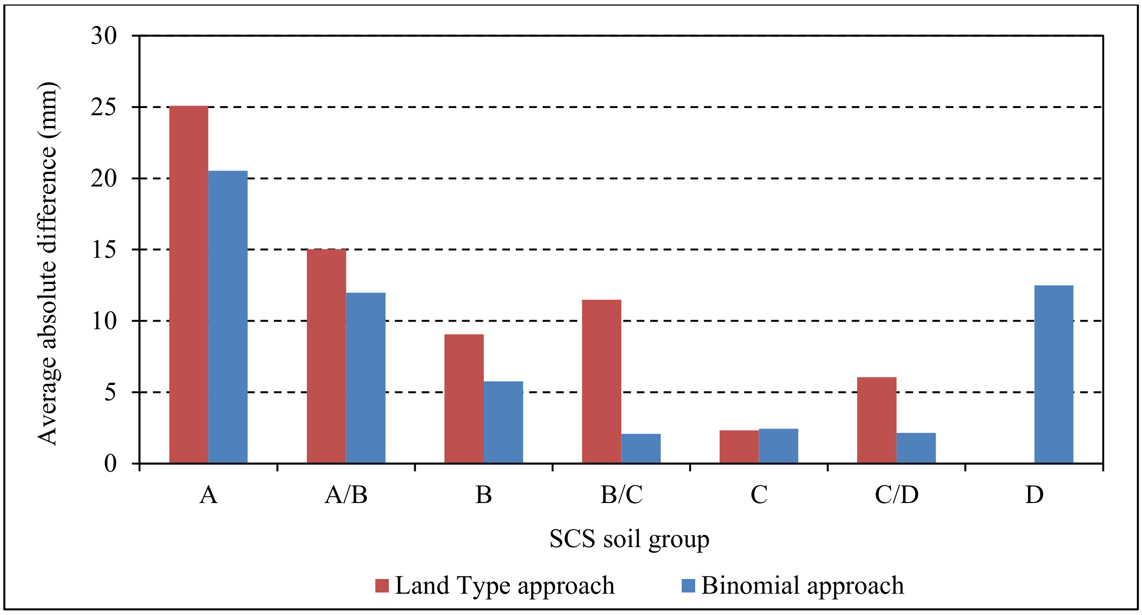


Figure 5.10 Average absolute difference between SCS-SA and *ACRU* design runoff simulations (averaged for the 2 – 100 year return periods) for the Land Type approach and the Binomial approach

Figure 5.11 depicts the average ratio change (averaged for all return periods from 2 – 100 years) going from SCS-SA soil group A to each of the subsequent soil groups A/B to D in the SCS-SA model and the *ACRU* model, for both the Land Type approach and the Binomial approach. The results presented in Figure 5.11 show that there is no significant difference in the ratio changes for the Land Type approach and the Binomial approach, with the ratio changes being considerably lower than the SCS-SA ratio changes. Therefore in terms of the runoff trends from the Binomial approach, there is no improvement compared to the Land Type approach. In addition, the deviation in the general runoff trend for SCS-SA soil group D, as highlighted above for the Binomial approach, is reinforced in Figure 5.11 where it is seen that for the Binomial approach the ratio change going from SCS-SA soil group A to D is less than the ratio change going from SCS-SA soil group A to C/D.

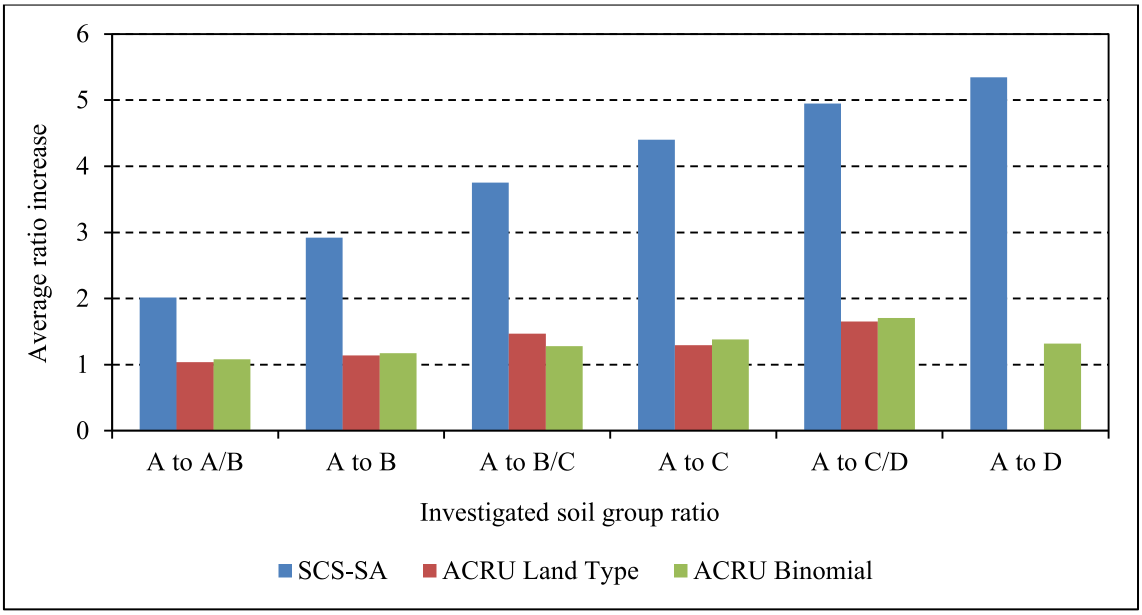


Figure 5.11 Average ratio change in design runoff depths calculated for each SCS-SA soil group (A/B to D) relative to SCS-SA soil group A for both the SCS-SA and *ACRU* simulation results (averaged for all return periods from 2 – 100 years), Land Type approach and Binomial approach

Further investigation was undertaken to account for the inconsistency obtained using the derived representation of a D soil in *ACRU*. Further analysis of the Binomial Soil Classification (Table 5.2) revealed that, in addition to the texture class and SCS-SA soil group, each soil series within the classification is assigned a symbol representing interflow potential. Interflow potential is a descriptor of inhibited drainage due to an impervious or a less pervious layer. The interflow potential is accounted for in the *ACRU* model by reducing the ABRESP/BFRESP fraction. The *ACRU* User Manual contains reduction factors for interflow potential as listed in Table 5.6.

Table 5.6 Suggested reductions of the ABRESP or BFRESP fractions of the soil according to "Interflow Potential" (Smithers and Schulze, 2004)

Interflow Potential	**Multiply ABRESP or BFRESP by**
0	1.0
X	0.6
XX	0.3

The interflow potential was used to adjust the ABRESP/BFRESP fractions for each SCS-SA soil group by percentage weighting, however, the adjustment did not change the trend of the results and the inconsistency was not improved. By adjusting the ABRESP/BFRESP fractions from Table 5.5, the fractions for a SCS-SA C/D soil and a D soil were very similar, with the response of the SCS-SA C/D soil being slightly higher. Therefore, in terms of runoff generation, this is a positive change since previously a SCS-SA C/D soil had a considerably lower response fraction compared to a SCS-SA D soil (Table 5.5), contributing to the high runoff observed for a SCS-SA C/D soil. The change, however, showed no appreciable change in the runoff trends. From this observation and the results discussed from both investigations to derive *ACRU* soil inputs that represent SCS-SA soil groups, it has been highlighted that the maximum soil water storage capacity and therefore the PO and PWP values are the over-riding parameters and runoff simulations are sensitive to these parameters.

In summary, the second investigation to attain a single set of *ACRU* variables to represent SCS-SA soil groups was, although improved, also not successful. Consequently, a final investigation was undertaken to link soil textural properties in *ACRU* to SCS-SA soil groups and the approach is elaborated on in the following section.

5.3 The Calibration Approach

In a third investigation to obtain *ACRU* soils information that represents SCS-SA soil groups, runoff simulations were performed in *ACRU* for each of the soil texture classes in Table 5.4. The objective was to identify the texture classes and arrangement of texture classes that would represent SCS-SA soil groups best, *i.e.* through a "calibration" process, in order to achieve similar trends in runoff by the *ACRU* model to those shown in Figure 5.1 for the SCS-SA model.

5.3.1 Methodology

Using the same configuration as described above, the *ACRU* model was "calibrated" to obtain similar simulation trends to those from the SCS-SA model shown in Figure 5.1, by firstly simulating runoff volumes for each of the soil texture classes in Table 5.4 using the *ACRU* model. The results from the *ACRU* simulations for the different texture classes were arranged in order of increasing runoff. The texture classes that represented each of the SCS-SA soil groups in Figure 5.1 best were then assumed to best represent SCS-SA soils in *ACRU, i.e.* the texture classes were arranged such that runoff volumes would increase consistently from an "A soil" texture class to a "D soil" texture class, thereby eliminating the inconsistencies obtained from the previous two approaches. This was performed in order to achieve similar trends in design runoff volumes simulated by the two models, *i.e.* to be able to eliminate the influence of soil information on the simulations between the two models. This would enable an investigation into which *ACRU* variables should be adjusted, and to what extent, in order to obtain similar simulations as the SCS-SA model for different management practices and hydrological conditions.

5.3.2 Results

Applying this approach the following texture classes, listed in Table 5.7, were found to represent each of the SCS-SA soil groups in *ACRU* best. The results from the simulations for these assigned texture classes are depicted in Figure 5.12. The results from Figure 5.12 show the same trend as the results from Figure 5.1 with an increase in runoff from SCS-SA A to D soils or Sa to SiCl soils simulated by the *ACRU* model.

Table 5.7 *ACRU* texture classes found to represent SCS-SA soil groups best

SCS-SA Soil Group	***ACRU* Calibrated Soil Textural Class**
A	Sand (Sa)
A/B	Loamy Sand (LmSa)
B	Sandy Loam (SaLm)
B/C	Loam (Lm)
C	Clay Loam (ClLm)
C/D	Sandy Clay Loam (SaClLm)
D	Silty Clay (SiCl)

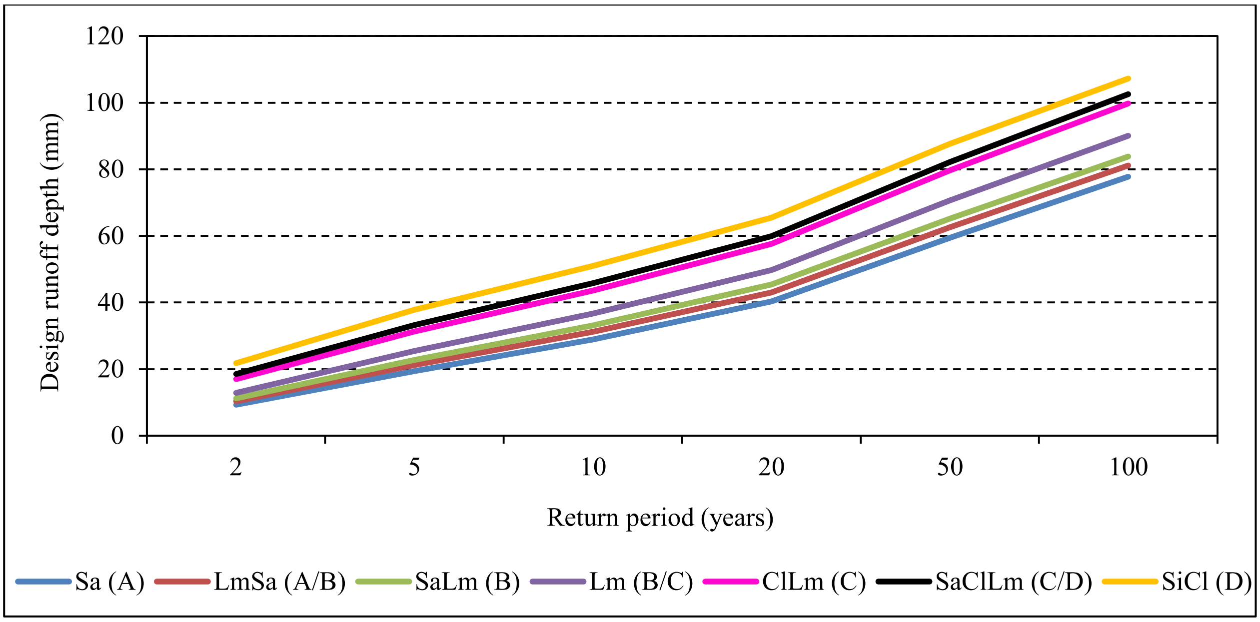


Figure 5.12 *ACRU* hydrological responses computed at specific return periods for a veld land cover, in fair hydrological condition for SCS-SA soil groups A – D, Calibration approach

In comparison to the previous two approaches, the average absolute differences between SCS-SA and *ACRU* design runoff volumes for the Calibration approach are consistently slightly smaller than those of the Land Type approach, except for SCS-SA soil group C (Figure 5.13). The average absolute differences for the Calibration approach, however, are generally slightly larger compared to the Binomial approach, except for SCS-SA soil group D (Figure 5.13). Therefore, in this regard, the results from the Calibration approach are not an improvement on the results from the previous two attempts. In terms of average ratio changes (Figure 5.14) for the Calibration approach there is a consistent ratio increase going from SCS-SA soil group A/B to D, however, it is again seen that there is no improvement in the runoff trends for the Calibration approach relative to the SCS-SA results. The ratio changes remain considerably lower than those obtained for the SCS-SA model. From the results and the various attempts made to relate SCS-SA soil groups to *ACRU* soil textural properties alone, it is clear that texture alone is not the only soil property that influences the determination of SCS-SA soil groups.

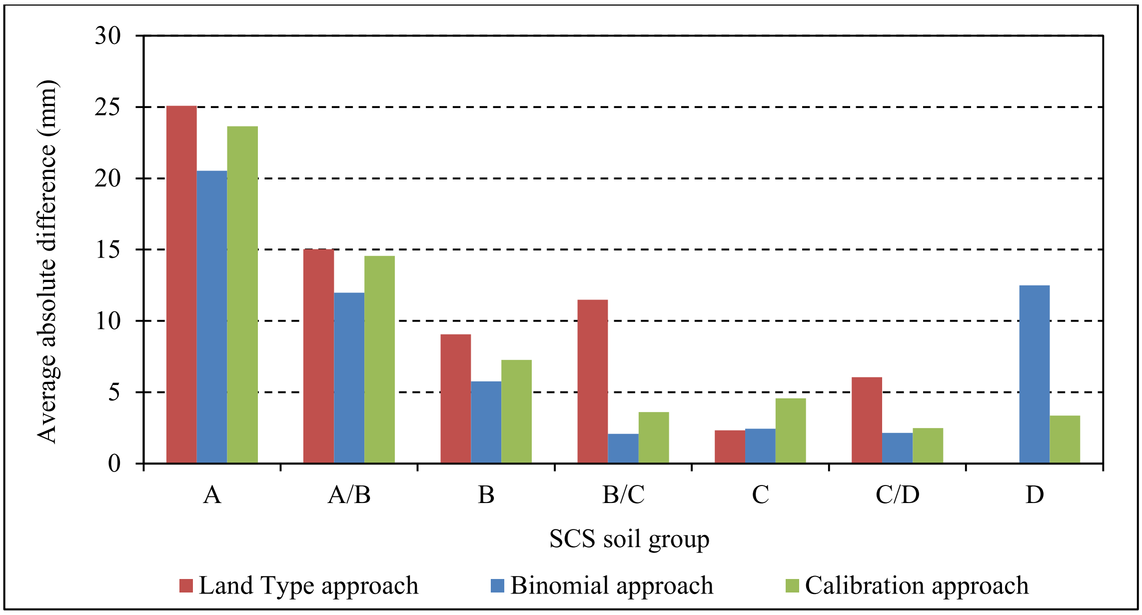


Figure 5.13 Average absolute difference between SCS-SA and *ACRU* design runoff simulations (averaged for the 2 – 100 year return periods) for the Land Type approach, Binomial approach and Calibration approach

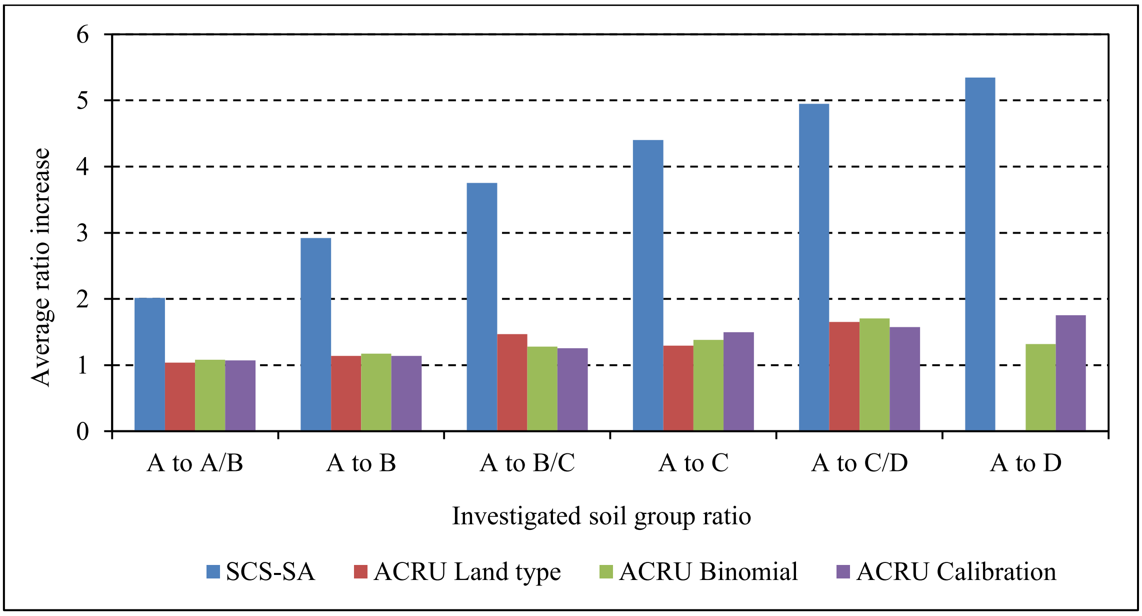


Figure 5.14 Average ratio change in design runoff depths calculated for each SCS-SA soil group (A/B to D) relative to SCS-SA soil group A for both the SCS-SA and *ACRU* simulation results (averaged for all return periods from 2 – 100 years), Land Type approach, Binomial approach and Calibration approach

Based on the above findings, it was necessary to perform a sensitivity analysis of *ACRU* model input variables, in order to identify which *ACRU* variables are most sensitive in terms of design flood estimates. The objective being to identify *ACRU* variables that may be used to represent SCS-SA soil groups more adequately in *ACRU*. The following chapter therefore elaborates on the sensitivity analyses conducted.

6. *ACRU* SENSITIVITY ANALYSIS

Schulze (1995) defines hydrological model sensitivity analysis as a measure of the effect of changes in model input, or model structure, on model output. After the failed attempts to represent SCS-SA soil groups in *ACRU*, it was realised that performing a sensitivity analysis of the *ACRU* input variables would be beneficial in identifying which variables are most sensitive in terms of the design runoff volumes output by the model.

In the *ACRU* Theory Manual (Schulze, 1995) sensitivity analyses were performed on various variables in the *ACRU* model using the following simple objective function and sensitivity rankings (Schulze, 1995):

$$\Delta O\% = \frac{(O - O_{Base})}{(O_{Base})} \times 100 \tag{6.1}$$

where

$\Delta O\%$ = percentage change in output,

O = output from a particular percentage change in selected input parameter,

O_{Base} = output from the base input

Sensitivity rankings used in the study (Schulze, 1995):

(i) Extremely sensitive (E): the percentage change in the output ($\Delta O\%$) is more than twice, *i.e.* 200%, that of the input parameter being tested ($\Delta I\%$), *i.e.* $\Delta O\% > 2(\Delta I\%)$.

(ii) Highly sensitive (H): the output change is more than the input change, but by less than 200%, *i.e.* $2(\Delta I\%) > \Delta O\% > \Delta I\%$.

(iii) Moderately sensitive (M): the relative output change is less than the relative input change, but by more than 50% of the input change, *i.e.* $\Delta I\% > \Delta O\% > 0.5(\Delta I\%)$.

(iv) Slightly sensitive (S): the output changes by between 10% and 50% of the input change, *i.e.* $0.5(\Delta I\%) > \Delta O\% > 0.1(\Delta I\%)$.

(v) Insensitive (I): the output changes by less than the 10% of the input change, *i.e.* $\Delta O\% < 0.1(\Delta I\%)$.

When performing a sensitivity analysis, several model output parameters may be investigated such as streamflow, stormflow, baseflow, soil water status and even design values (Schulze, 1995). For each selected input variable a base run is performed (O_{Base}), as the reference output. Percentage changes to the selected input variable are then made, recording the new output value (O). The percentage change in the output ($\Delta O\%$) from the base output (O_{Base}) is then calculated using Equation 6.1. The sensitivity of the percentage change is then ranked using the sensitivity ranking described previously.

Schulze (1995) reports on the results of a sensitivity analysis conducted by Angus (1989) applying the procedure outlined above. The model output investigated was total streamflow, investigated at a single location, *i.e.* Cedara in the KZN Midlands. The results from the sensitivity analysis are summarised in Table 6.1.

Table 6.1 Summarised results of the *ACRU* sensitivity analyses conducted by Angus (1989) based on the effect of varying input parameters on total streamflow (Schulze, 1995)

Parameter*	**Sensitivity of Parameter when**		**Comment**
	Reduced	**Increased**	
RAINFALL	Extreme	Extreme	Most sensitive parameter
APAN	High	High	
DEPAHO, DEPBHO	High	Slight	More sensitive when shallow
ITEXT	Slight	Slight	
ABRESP	Slight	Slight	
BFRESP	Slight	Slight	
CONST	Slight	Slight	Baseflow very sensitive
CAY	High	High	Identical impact as APAN
ROOTA	Slight	Slight	Baseflow very sensitive
VEGINT	Slight	Slight	
SMDDEP	High	Slight	H when *SMDDEP*< 0.15m
COIAM	Moderate	Slight	

**RAINFALL* – Daily rainfall (mm); *APAN* – Daily A-pan equivalent evaporation (mm); *DEPAHO/DEPBHO* – Depth of the A and B horizon (m); *ITEXT* – Eleven texture classes defined in the *ACRU* model; *ABRESP* - Fraction of soil water above DUL that drains from the A horizon into the B horizon of a soil; *BFRESP* - Fraction of soil water above DUL that drains from the B horizon of the soil into the intermediate groundwater zone; *CONST* – Fraction of plant available water where actual evaporation drops below maximum evaporation; *CAY* – Average monthly crop coefficients for vegetation; *ROOTA* – Fraction of active root mass in the A horizon of the soil; *VEGINT* – Interception loss by vegetation ($mm.day^{-1}$); *SMDDEP* – Critical response depth of the soil; *COIAM* – Coefficient of initial abstraction.

The results show that the model was found to be extremely sensitive to Rainfall and highlights the importance of accurate and representative rainfall data when simulating runoff in the *ACRU* model. The following variables were found to be highly sensitive *APAN*, a reduction in *DEPAHO/DEPBHO*, *CAY* and a reduction in *SMDDEP*. All other variables investigated were found to be only slightly sensitive, with the exception of a reduction in the *COIAM* which displayed moderate sensitivity. Schulze (1995) conducted an additional sensitivity analysis of the *ACRU* model to input under varying environmental conditions, *i.e.* at different locations across the country. The same procedure as described above was once again implemented, however, in this case the output investigated was Mean Annual Streamflow (MAR). In the analysis, however, only three input variables were investigated including Rainfall, *SMDDEP* and E_m. The results once again highlighted that the model is highly sensitive to changes in Rainfall and *SMDDEP*, particularly a decrease in *SMDDEP*. The model was also found to be sensitive to changes in E_m, however, to a lesser extent compared to the Rainfall and *SMDDEP* sensitivity. It was also found that the sensitivity of the model to these three inputs varies with location in certain cases.

A similar sensitivity analysis procedure to the approach adopted by Angus (1989) and Schulze (1995) was followed in this study, with their results used to guide which variables were selected. It is, however, important to note that in this study the sensitivity of the model to design runoff volumes is being investigated and not total streamflow or MAR, as investigated by Angus (1989) and Schulze (1995). Therefore it cannot be assumed that because the variables were found to be sensitive in terms of total streamflow and MAR, they will also be sensitive in terms of design runoff volumes.

For consistency the same objective function (Equation 6.1) and sensitivity ranking as described above is used to assess the sensitivity of simulated design runoff volumes in the *ACRU* model to percentage changes in selected input variables. The percentage change in output for each percentage input change is averaged over all return periods, from 2 – 100 years, to provide a single representative average for comparison to the percentage changes from the other inputs investigated.

The results from the sensitivity analyses conducted by Angus (1989) and Schulze (1995) showed that the *ACRU* model is highly sensitive to *SMDDEP* in terms of total streamflow and MAR, particularly for a reduction in the *SMDDEP*. Based on these findings, it is important to assess if the *ACRU* model is equally sensitive to changes in *SMDDEP* in terms of simulated design runoff volumes. Furthermore, as identified in the review of the *ACRU* model (Chapter 3.2), another important variable that directly influences the partitioning of runoff volumes on a daily basis is the *QFRESP* coefficient. The sensitivity of the *ACRU* model to *QFRESP*, however, was not investigated in the sensitivity analyses presented in the *ACRU* Theory Manual. Nonetheless since *QFRESP* is directly associated with the partitioning of runoff volumes, it was identified as an important variable to include in the sensitivity analysis. The *QFRESP* and *SMDDEP* variables are difficult to measure or quantify and have generally been estimated through calibration, with default values generally suggested to the user for the *ACRU* model.

Figure 6.1 displays the average percentage changes in simulated design runoff volumes (averaged for all return periods from 2 – 100 years) for various percentage changes in *SMDDEP*, from an initial default depth of 0.25m, *i.e.* the A horizon depth. Once again the same model set-up as used in the previous simulations was applied, using an intermediate clay loam soil textural class and changing only the *SMDDEP* by the percentages depicted in Figure 6.1. The results reveal that the *ACRU* model is moderately sensitive to changes in *SMDDEP* in terms of design runoff estimates, *i.e.* $\Delta I\% > \Delta O\% > 0.5(\Delta I\%)$. Therefore in terms of *SMDDEP* the results are similar to those obtained by Angus (1989) and Schulze (1995), where the sensitivity ranged from slightly sensitive to highly sensitive (Table 6.1). Angus (1989) and Schulze (1995) found the *ACRU* model to be particularly sensitive to decreases in *SMDDEP*, particularly when *SMDDEP* < 0.15m (Table 6.1). This, although not strongly evident, is also apparent in the results presented in Figure 6.1, where the average percentage change for a decrease in *SMDDEP* by 50% is noticeably higher (34%) compared to the average percentage change for an increase in *SMDDEP* by 50% (-27%). The trend is likely only weakly evident since the initial *SMDDEP* was set at a relatively high value and therefore even with a 50% reduction in *SMDDEP*, the *SMDDEP* is only slightly lower than the 0.15m found by Angus (1989) to be a threshold for high sensitivity, *i.e.* 0.13m. The results, nonetheless, show that the *ACRU* model is sensitive to changes in *SMDDEP* in terms of the design runoff simulations.

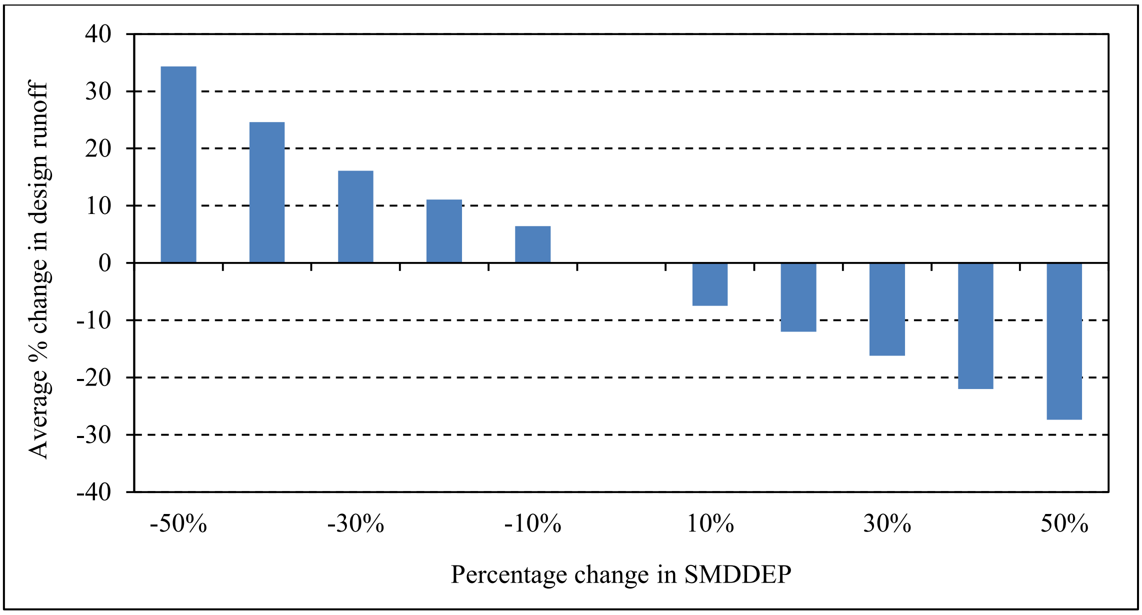


Figure 6.1 Average percentage changes in simulated runoff depths (averaged for all return periods from 2 – 100 years) for percentage changes in *SMDDEP* from the initial default value

As stated above, *SMDDEP* is generally defaulted to the depth of the A horizon, however, within the *ACRU* manual (Schulze, 1995) suggestions have been made to adjust *SMDDEP* dependent on, *inter alia*, the climate, vegetation and soil properties, *i.e.* MAP and rainfall intensity, vegetation density linked to rainfall and MAP, and dystrophic, mesotrophic or eutrophic soils (Schulze, 1995; Smithers and Schulze, 2004). Therefore referring back to Chapter 3 on hydrological modelling and the issues on uncertainties in hydrological modelling, it is important to highlight that consideration of adjusting *SMDDEP* to possibly represent SCS-SA soil groups in *ACRU* is a valid option, *i.e.* since *SMDDEP* directly represents soil properties such as the permeability, with eutrophic soils generally being shallow, poorly leached and poorly drained soils, while dystrophic soils are deeper, highly leached and well drained soils. Therefore, since SCS-SA soil groups are defined by infiltrability and permeability and *SMDDEP* also accounts for soil water permeability, adjustment of *SMDDEP* to represent SCS-SA soil groups is hydrologically and conceptually sound and justifiable.

QFRESP is a variable within the *ACRU* model that receives little attention and is generally defaulted to a value of 0.3, *i.e.* through prior experience, for catchment sizes of approximately 50km^2 and below (Schulze, 1995). It is important to once again emphasise that the *QFRESP* variable only influences the timing of the surface runoff component, on the total runoff exiting a catchment on a specific day. Therefore using the default value of 0.3, only 30% of the surface runoff (*STORMF*) generated from a rainfall event on a specific day exits the catchment on that day. The remainder is added to the next days' accumulated *STORMF* and is released as a decay function. Similar to the *SMDDEP* variable, *QFRESP* is likely to be directly influenced by the soil and vegetation properties within a catchment as well as the catchment size. In terms of the latter, small catchment sizes, *i.e.* < $2km^2$, have generally been accepted to release all their *STORMF* on the same day as the rainfall event, resulting in the selection of a *QFRESP* coefficient of 1 (Schulze, 1995; Lumsden and Jewitt, 2000). Royappen (2002), however, simulating streamflow from several small research catchments in South Africa, attempted to link *QFRESP* and the Coefficient of Baseflow Response (*COFRU*) to physical catchment characteristics, realising that these parameters are not explicitly physically based and that improved guidelines of initial parameter values are required. Although the findings were inconclusive in terms of linking these variables to catchment specific characteristics, several small research catchments (< $2km^2$) were found to produce optimal streamflow simulations applying *QFRESP* values well below 1, therefore questioning the assumption that for small catchments a *QFRESP* value of 1 is acceptable. It is highly likely that *QFRESP* may be strongly linked to soil as well as vegetation properties and not simply catchment area. Further research is needed to assess the impact of catchment area along with other characteristics such as soil and vegetation properties on the *QFRESP* value selected. The importance of the above comments and subsequent need for accurate estimates of *QFRESP* are particularly evident when observing the sensitivity of the *ACRU* model to changes in the *QFRESP* variable (Figure 6.2). Once again the same model set-up as used in the previous simulations was applied, using an intermediate clay loam soil textural class and changing only the *QFRESP* by the percentages depicted in Figure 6.2. In terms of the sensitivity ranking, the *ACRU* model is also moderately sensitive to changes in the *QFRESP* variable. There is no difference in the sensitivity of the *ACRU* model to increases or decreases in the *QFRESP* variable. Comparison of Figure 6.2 and Figure 6.1, however, reveals that the *ACRU* model is more sensitive to changes in the *QFRESP* variable compared to changes in the *SMDDEP* variable.

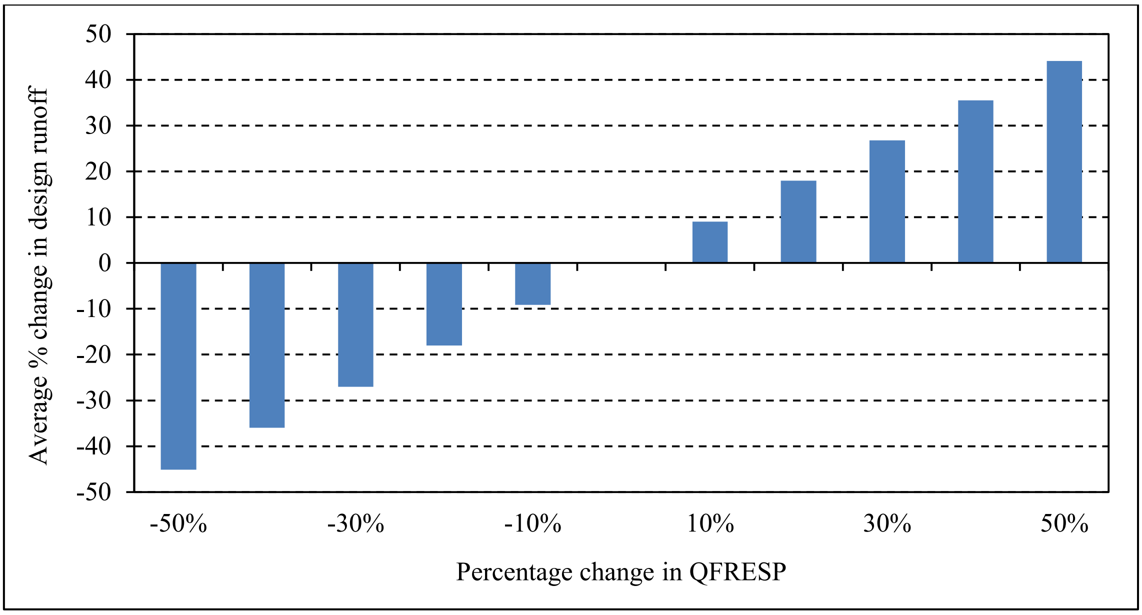


Figure 6.2 Average percentage changes in simulated runoff depths (averaged for all return periods from 2 – 100 years) for percentage changes in *QFRESP* from the initial default value

Although the estimation of design runoff depths using the *ACRU* model is more sensitive to the *QFRESP* variable in terms of the design runoff volumes simulated, it needs to be emphasised again that adjusting the *QFRESP* variable does not change the accumulated volume of surface runoff generated, but only influences the timing and magnitude of the runoff volumes. Figure 6.3 depicts this graphically where the cumulative runoff for one rainfall season is plotted for several of the percentage changes in *QFRESP* depicted in Figure 6.2. Analysis of Figure 6.3 reveals that there are clear differences in the cumulative runoff volumes simulated during the rainfall season, *i.e.* 01/08/1951 – 01/10/1951, however, by the end of the rainfall season (after the 01/12/1951) the cumulative runoff volumes are identical. The *QFRESP* variable therefore does not change the cumulative amount of runoff generated over an entire simulation period but influences the timing and magnitude of flood volumes over the rainfall season. In terms of DFE, the accurate estimation of these volumes however is of vital importance to the structural integrity of hydraulic infrastructure. Consequently a system to accurately estimate *QFRESP* could potentially improve the estimation of design runoff depths using the *ACRU* model.

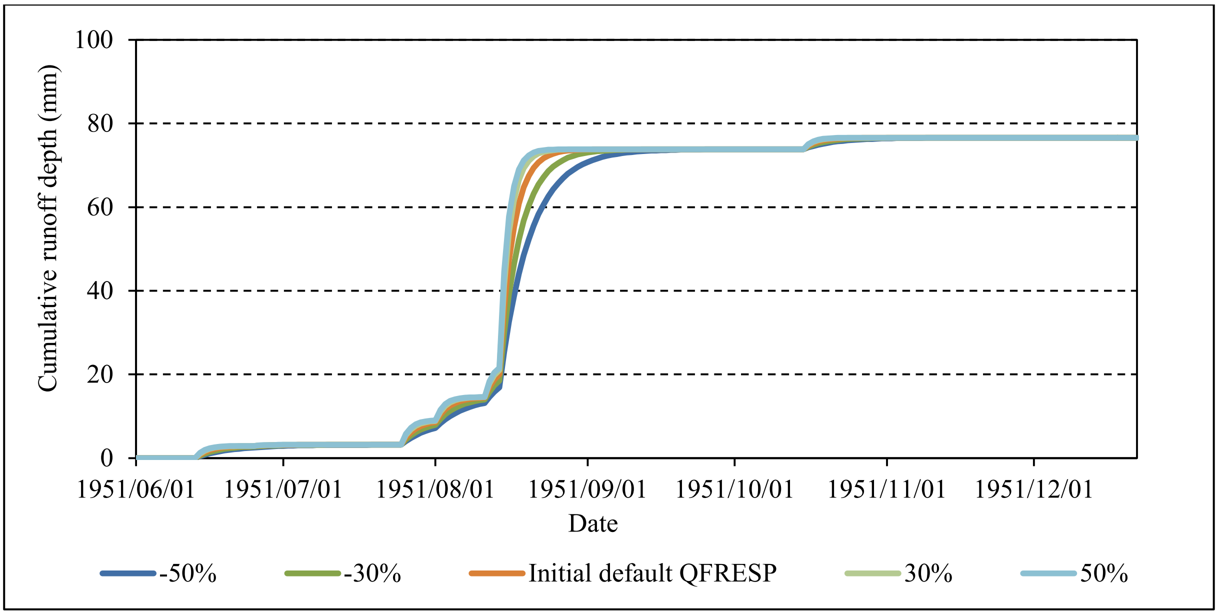


Figure 6.3 Cumulative runoff depths simulated for the initial default *QFRESP* value and specific percentage changes in *QFRESP* for one rainfall season

In contrast, adjustment of the *SMDDEP* variable influences the actual amount of runoff simulated. Figure 6.4 shows how changing *SMDDEP* for the same time period depicted in Figure 6.3 changes the cumulative amount of runoff generated. Consequently, in terms of an entire simulation period, changing *SMDDEP* has a considerable influence on the total amount of surface runoff generated. Therefore, in summary, changing *QFRESP* has a greater influence on the design runoff values output by the *ACRU* model compared to changing *SMDDEP*. However, changing *SMDDEP* changes the total amount of runoff generated in a cumulative sense, while changing *QFRESP* only influences the partitioning of runoff volumes and not the cumulative amount of runoff generated. The timing and magnitude of these volumes, however, are extremely important and are dependent on both the *QFRESP* and *SMDDEP* values input into the model. Consequently, both *QFRESP* and *SMDDEP* are sensitive model variables and can both potentially be used to represent SCS-SA soil groups in *ACRU*.

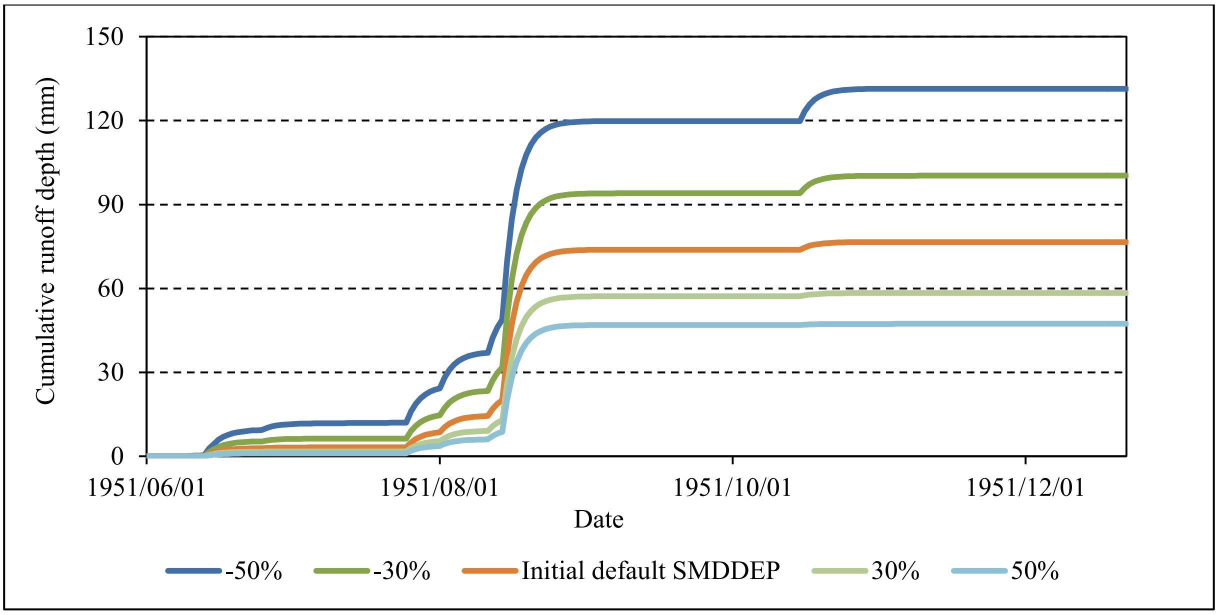


Figure 6.4 Cumulative runoff depths simulated by the *ACRU* model for the initial default *SMDDEP* value and specific percentage changes in *SMDDEP* for one rainfall season

In addition to representing SCS-SA soil groups in *ACRU*, the *ACRU* hierarchical classification needs to include sub-classes for hydrological condition and management practice. Therefore, additional variables need to be adjusted to represent these conditions. The sensitivity of several of the variables that represent vegetation characteristics were therefore investigated, in order to identify if they could be utilised to represent these different conditions. This was deemed to be reasonable as vegetation properties are expected to have a considerable influence on runoff responses and if these variables are found to be sensitive, in terms of simulated design runoff volumes, they could possibly be used to represent hydrological condition and management practice in the *ACRU* model to achieve similar responses to those within the SCS-SA model. Again guided by the results of the sensitivity analysis conducted by Angus (1989) and Schulze (1995), the following variables representative of vegetation characteristics were considered, including (i) average monthly *CAY*, K_{cm}; (ii) interception loss (mm.rainday^{-1}) by vegetation (*VEGINT*), given month-by-month; (iii) percentage surface cover (mulch, litter, *etc.*) input month-by-month (*PCSUCO*); and (iv) the coefficient of initial abstraction (*COIAM*).

CAY is a coefficient that varies month to month and is multiplied by the reference potential evaporation to calculate the actual amount of water transpired from the plant (Schulze, 1995).

CAY is dependent on the type of vegetation, development stage, *i.e.* in terms of agricultural crops, and season. Angus (1989) and Schulze (1995) found the *ACRU* model to be highly sensitive to changes in *CAY* (Table 6.1). Figure 6.5, however, shows that the *ACRU* model is insensitive to *CAY* in terms of the design runoff volumes simulated. The model is, however, more sensitive to a decrease in the *CAY* variable, *i.e.* reducing the amount of transpiration, nevertheless even then the sensitivity is negligible, *e.g.* compared to the sensitivity of the model to the *QFRESP* and *SMDDEP* variables analysed previously.

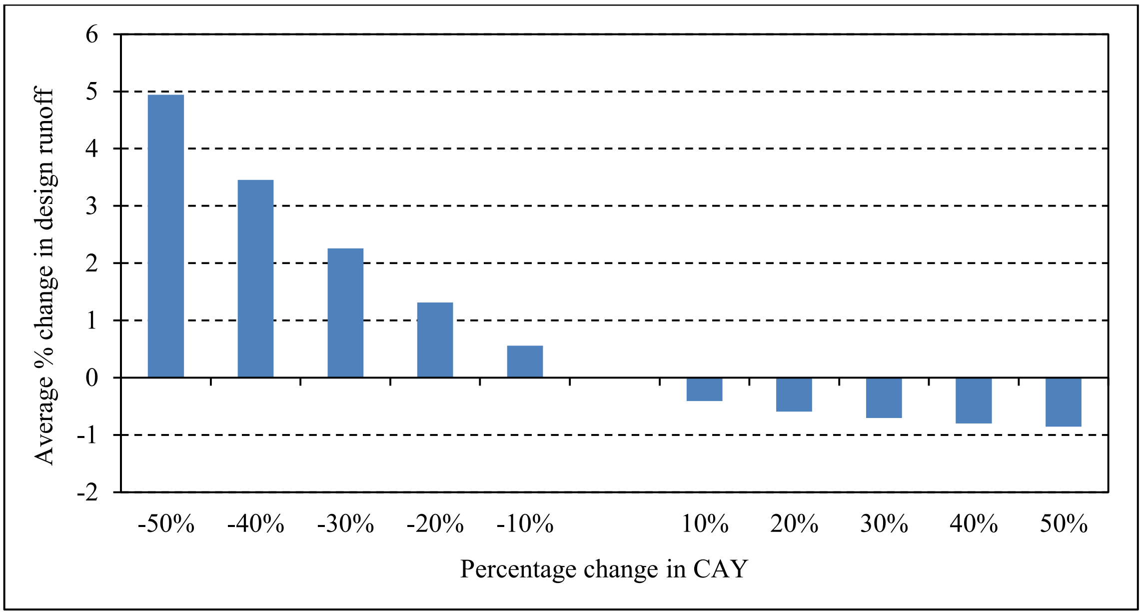


Figure 6.5 Average percentage changes in simulated runoff depths (averaged for all return periods from 2 – 100 years) for percentage changes in *CAY* from the initial default values

The *VEGINT* variable determines the amount of rainfall intercepted by vegetation per rain-day, again dependent on the vegetation properties. This intercepted water is evaporated first on the succeeding day and subtracted from the reference potential evaporation, which is recalculated and the residual used to determine the amount of water evapotranspirated from the vegetation and the soil (Schulze, 1995).

PCSUCO represents the percentage surface cover, excluding the vegetation itself which, when the correct evapotranspiration option is used (*EVTR2*), regulates the amount of water evaporated from the soil, *i.e.* with a high percentage cover reducing the amount of water evaporated. In the *ACRU* model, two evapotranspiration options are available: Option 1

(*EVTR1*) and Option 2 (*EVTR2*). *EVTR1* groups Soil Water Evaporation (*Es*) and Plant Transpiration (*Et*) together as a single output. In this scenario the amount of evapotranspiration is controlled by only the *CAY* variable, *i.e.* which is used to partition *Er* into *Et* and *Es* internally within the model, and the soil water content (Schulze, 1995). When using *EVTR2*, *Es* and *Et* are calculated separately and are output as two separate entities. Similar to *EVTR1*, the *CAY* variable is again used to partition *Er* into *Et* and *Es* internally within the model, however, in this case the *PCSUCO* variable is used to further refine the amount of *Es*. Conceptually it is more correct to calculate *Es* and *Et* separately and to factor in the effect of *PCSUCO* on *Es*. *EVTR2*, however, is often not selected since default values of *PCSUCO* are often not available and estimating this variable is difficult unless the modeller has visited the site and can estimate a value representative of the area under consideration. At this juncture, it is important to state that for all the *ACRU* simulations performed to this point, *EVTR2* has been used. The *PCSUCO* value used, *i.e.* for the grassland set-up, is the default value assigned to The Southern Tall Grassveld (Acocks #65). The Acocks (1988) natural vegetation within the COMPOVEG database, built into the *ACRU* model, is one of the few land use groups that have been assigned default *PCSUCO* values, many of the other land use classes have not been assigned values or the values have been assigned inconsistently. This is an additional issue that needs to be addressed in further research, however, it is not within the scope of this research project. For the remaining simulations reported on in this document, *EVTR2* has been used with the default values when available, otherwise the recommended value of zero suggested within the *ACRU* model was used, *e.g.* for agricultural crops, assuming that *CAY* will adequately partition the evapotranspiration component into *Et* and *Es*.

Angus (1989) and Schulze (1995) found the *ACRU* model to be slightly sensitive to changes in the *VEGINT* variable (Table 6.1). The sensitivity of the *PCSUCO* variable, a relatively newly introduced variable to the *ACRU* model, was not investigated. Figure 6.6 and Figure 6.7 show that the model is insensitive to these variables in terms of simulated design runoff volumes. In both cases, the *ACRU* model is equally as sensitive to percentage increases and decreases in the two variables.

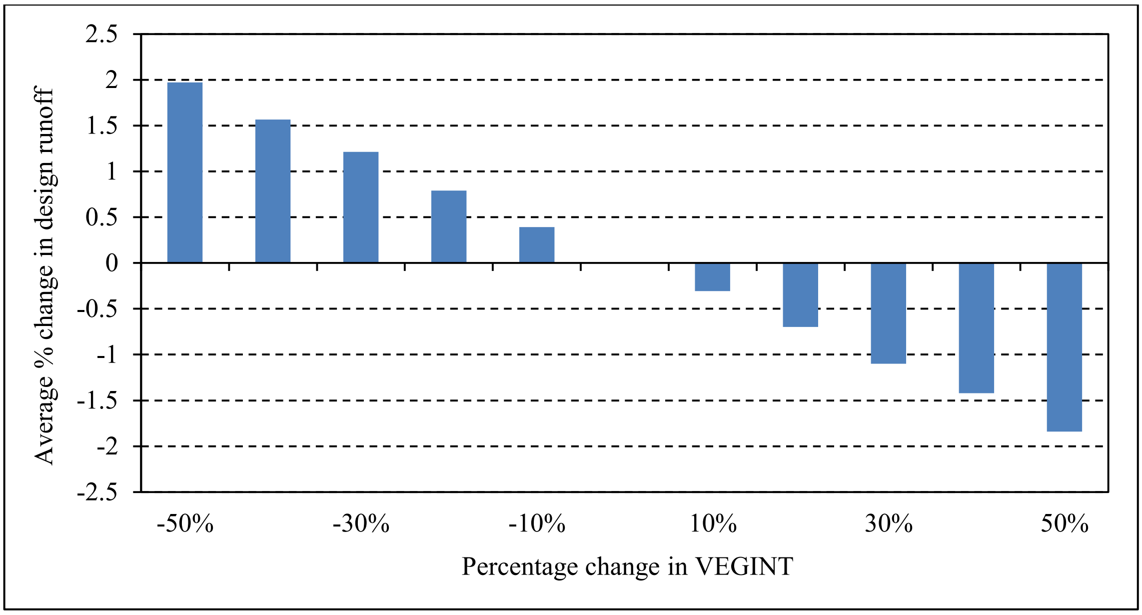


Figure 6.6 Average percentage changes in simulated runoff depths (averaged for all return periods from 2 – 100 years) for percentage changes in *VEGINT* from the initial default values

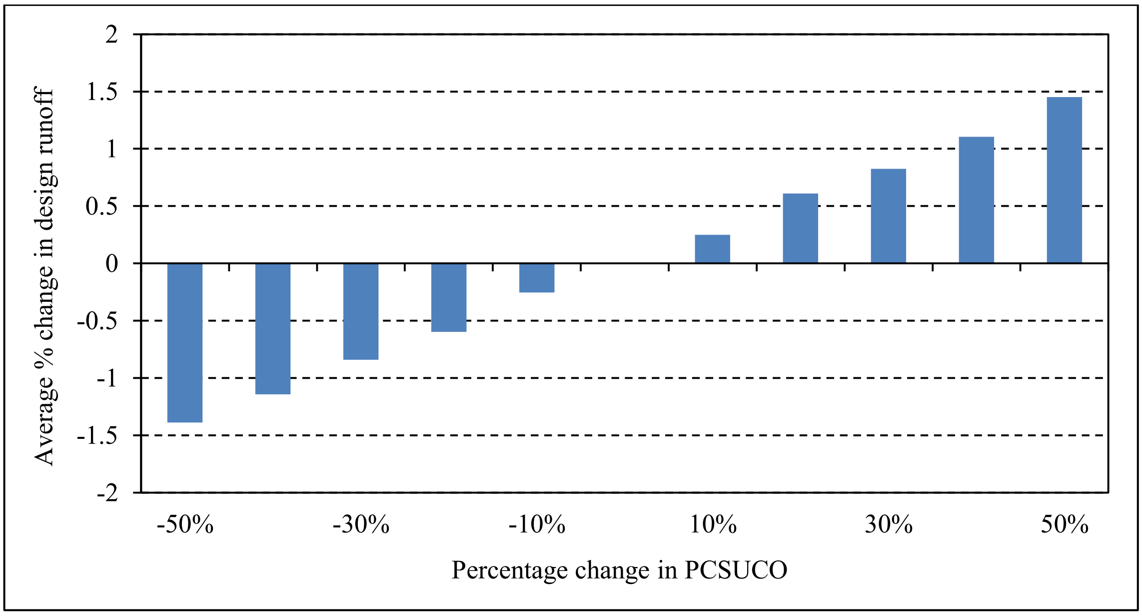


Figure 6.7 Average percentage changes in simulated runoff depths (averaged for all return periods from 2 – 100 years) for percentage changes in *PCSUCO* from the initial default values

The insensitivity of the *ACRU* model to the *CAY*, *VEGINT* and *PCSUCO* variables, in terms of design runoff volumes, can be explained through consideration of the following realisations. Design runoff volumes are computed from the largest daily runoff volumes taken from each year. The change in runoff, however, on any given day and particularly for a design event, due to a change in the *CAY*, *VEGINT* and *PCSUCO* variables is therefore negligible since these variables are fine tuners of the *S* value in the SCS (1956) runoff equation (Equation 3.1), *e.g.* on any given day they only change the *S* value by a small amount. To observe noticeable changes in design runoff volumes a large change to the *S* value on a daily basis has to occur, *i.e.* changing *SMDDEP*, or alternatively the partitioning of the daily runoff volumes needs to change, *i.e.* changing *QFRESP*. The change in simulated runoff for variables such as *CAY*, *VEGINT* and *PCSUCO* only becomes significant when measuring total streamflow or MAR, where the change is measured over an entire simulation period.

The *COIAM* variable in the SCS (1956) runoff equation (Equation 3.1) is a variable that (i) was calibrated for both the SCS and SCS-SA models; (ii) is a generalised constant that determines the amount of water abstracted from a rainfall event; and (iii) is linked to *S*. It therefore has a direct influence on the amount of runoff generated. In the *ACRU* model, the *COIAM* is input month-by-month and accounts for the following: land use/land cover, vegetation characteristics, *i.e.* development stage, rainfall seasonality and rainfall intensity (Topping, 1992). Since this variable already accounts for several other properties, it was considered preferable to avoid using this variable, however, it was still evaluated in the sensitivity analysis to determine if the model is sensitive to the variable in terms of design runoff volumes. Angus (1989) and Schulze (1995) found the *ACRU* model to be slightly sensitive to an increase in the *COIAM* and moderately sensitive to a decrease in the *COIAM* variable (Table 6.1). Figure 6.8 shows that the model is slightly sensitive to the *COIAM* in terms of the design runoff volumes simulated. Additionally, the model is equally sensitive to both an increase and a decrease in the *COIAM* variable (Figure 6.8). The sensitivity of the model to the *COIAM* is, however, once again negligible compared to the *QFRESP* and *SMDDEP* variables. The greater sensitivity of the *ACRU* model to the *COIAM* variable, compared to the *CAY, VEGINT* and *PCSUCO* variables above, is as a result of the direct relationship between the *COIAM* and the *S* value in the SCS (1956) runoff equation (Equation 3.1). The *COIAM* is multiplied by the *S* value and therefore has a relatively strong influence on the daily runoff volumes generated in the *ACRU* model and hence the design runoff volumes. The sensitivity, however, as identified from Figure 6.8 is only slight. With regard to the cumulative runoff, adjusting *CAY*, *VEGINT* and *PCSUCO* results in very slight differences in the cumulative runoff volumes simulated within the *ACRU* model. On the other hand, adjustment of the *COIAM* results in considerable differences in the cumulative runoff volumes simulated. Therefore, although changing the *COIAM* only has a slight influence on the design runoff volumes simulated, it has a significant influence on the cumulative runoff volume obtained for an entire simulation period, *e.g.* several years.

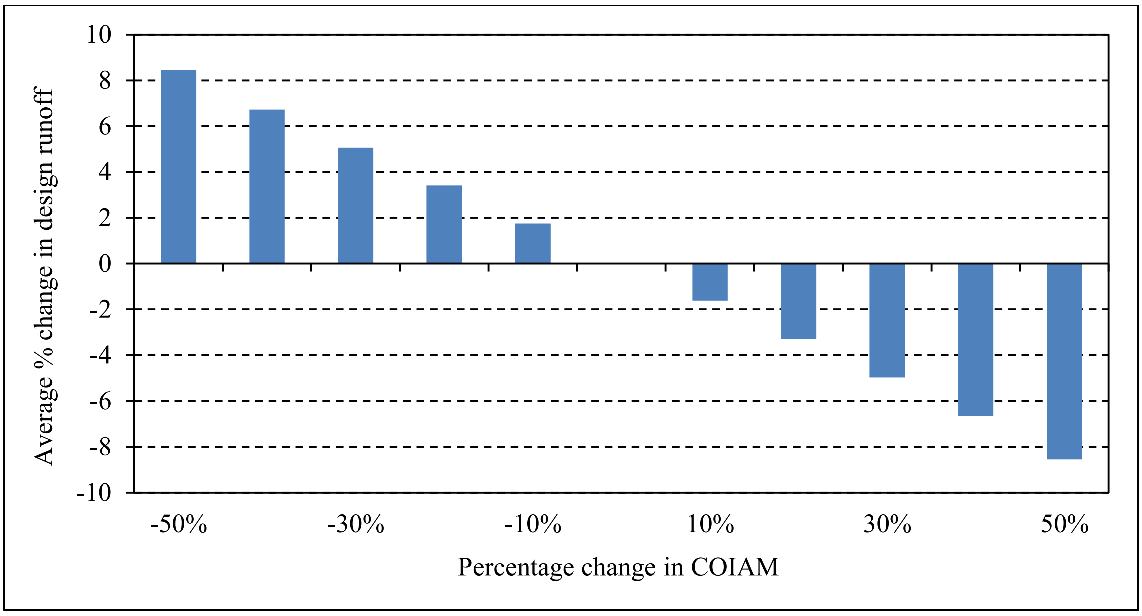


Figure 6.8 Average percentage changes in simulated runoff depths (averaged for all return periods from 2 – 100 years) for percentage changes in the *COIAM* from the initial default values

In summary, changing any of the four vegetation related variables analysed above will have a relatively negligible influence on design runoff volumes simulated by the *ACRU* model. Consequently, the possibility of using these variables to represent land management practice and hydrological condition in the *ACRU* model is not promising. Although the model is not sensitive to these variables, it is nonetheless conceptually correct to adjust these variables to represent changes in hydrological condition and management practice, since in reality these variables would change based on a change in hydrological condition or management practice. If, however, as stated above, the adjustment of these variables alone does not result in differences in runoff responses similar to those obtained within the SCS-SA model, it may be necessary to supplement the adjustments with alterations to additional variables that are conceptually and scientifically suitable to represent these changes.

Having analysed the sensitivity of the *ACRU* model to some of the variables important to runoff generation, the following chapter documents how these variables were utilised to achieve similar runoff responses in the *ACRU* model to those obtained in the SCS-SA model for different hydrological soil groups, hydrological conditions and land management practices. It is important to note at this point that in the following chapter it was necessary to calibrate the *ACRU* runoff responses against the SCS-SA runoff responses in order to obtain similar trends in runoff for SCS-SA soil groups, management practices and hydrological conditions in the *ACRU* model to those obtained in the SCS-SA model. Subsequently, obtaining similar runoff volumes in both models became the main objective of the analyses to follow. It is acknowledged that this is not the most ideal scenario, *i.e.* attempting to mimic the estimated runoff responses between two models, however it is necessary in order to identify how the same runoff trends, as obtained from the SCS-SA model, may be represented in the *ACRU* model. Therefore it is again important to emphasise that in the investigations to follow, the main objective is to optimise the similarity between SCS-SA and *ACRU* design runoff volumes for each SCS-SA land cover class and SCS-SA soil group investigated.

7. SCS-SA TO *ACRU* REVISED

In the previous chapter, the sensitivity of design flood estimates using the *ACRU* model to several input variables was examined. The results revealed that the model is particularly sensitive to two variables, namely *QFRESP* and *SMDDEP*, in terms of simulated design runoff volumes. It is, however, emphasised that the sensitivity of the model in this research is directed to design runoff volumes output from extreme events, *i.e.* the model may or may not be sensitive to the variables analysed in terms of MAR or monthly and annual streamflow totals for example.

The following sections contain the results of investigating how *QFRESP* and *SMDDEP* may be used to represent SCS-SA soil groups, land cover, hydrological condition and management practice in the *ACRU* model, all of which are accounted for in the SCS-SA model by one variable, the catchment CN. The consistency of the variables in representing these conditions is tested firstly for the hypothetical catchment as utilised previously, *i.e.* Quinary V11L3, Bergville, KZN (Figure 5.4), followed by two additional hypothetical catchments situated within selected quinary catchments in the Mpumalanga and Western Cape Provinces of South Africa. These additional analyses were performed in order to assess the performance of the relationships between SCS-SA catchment CNs and the variables selected under different climatic conditions.

7.1 Initial Investigation: KwaZulu-Natal

As alluded to in the introduction to this chapter, a relationship between SCS-SA CNs and the *QFRESP* and *SMDDEP* variables was firstly investigated for Quinary V11L3. As used in the previous simulations, a veld in fair condition was once again initially used. In terms of the soil properties used to represent SCS-SA soil groups in the *ACRU* model, those derived in the Binomial Soil Classification approach (Section 5.2) were used, however, in this case additional adjustments were made to the *QFRESP* and *SMDDEP* variables until, through calibration, the *ACRU* simulation results were similar to the SCS-SA results for a similar land cover class and hydrological condition. The results from the Binomial approach, although still containing inconsistencies, were selected in preference to the results from the Calibration approach to avoid the situation where a calibration is performed on another calibration. In addition, the results from the Binomial approach were derived scientifically, and in terms of the similarity of the *ACRU* results to the SCS-SA results the most comparable results were obtained when the Binomial approach was used in the *ACRU* simulations (Figure 5.13). The following sections present the results for a veld/grassland land cover firstly in fair condition, then in poor condition and thirdly in good condition, followed by the simulation results for a row crop/maize land cover all within the same hypothetical catchment, Quinary V11L3, Bergville, KZN. These land cover classes were selected since large areas of South Africa are under grassland/natural vegetation, while maize is extensively cultivated particularly in the eastern parts of the country.

7.1.1 Veld/Grassland land cover in fair condition

Figure 7.1 compares the simulation results from the SCS-SA model to those from the *ACRU* model with adjustment to *QFRESP* only. The SCS-SA simulation results for a veld/grassland land cover, as depicted in Figure 5.1, are again used in the following analyses. However, the results for each SCS-SA soil group are reviewed individually, *e.g.* Figure 7.1 displays only the SCS-SA simulation results for SCS-SA soil group A (SCS A Fair). In terms of the *ACRU* simulations, the same model set-up as used before for a veld/grassland land cover was used, *i.e.* with the soil textural properties derived in the Binomial approach (Section 5.2), however, in this case as a starting point the *QFRESP* variable was set to 0.30 (labelled *QFRESP* = 0.30), *i.e.* the general default value for catchments of approximately $50km^2$ and smaller. This was done based on the findings presented in Chapter 6 where the assumption that small catchments, less than $1km^2$, should be assigned a *QFRESP* value of 1, was reviewed in terms of the results presented by Royappen (2002). Analysis of the results (Figure 7.1) shows that using a *QFRESP* value of 0.30 produces simulation results far more comparable to those of the SCS-SA model for a SCS-SA A soil, compared to when a *QFRESP* value of 1 is used. Through calibration, the most appropriate *QFRESP* value to represent a SCS-SA A soil group for a veld in fair condition was found to be 0.32. Using a *QFRESP* value of 0.32, the simulation comparison improved slightly compared to when a value of 0.30 was used. Further increasing the *QFRESP* value, however, to 0.38 (Figure 7.1) resulted in a less similar simulation comparison, *i.e.* where the return period events from 2 – 80 years are all over simulated, with only the return period events from 80 – 100 years producing similar simulation results to the SCS-SA results. Using a *QFRESP* value of 0.32 also does not produce a perfect simulation comparison, with a slight over simulation at the lower return periods and slight under simulation at the higher return periods, however, the overall fit is acceptable and considered to be the most optimal fit attainable. *SMDDEP* was not investigated in the first assessment for SCS-SA soil group A (Figure 7.1), since the simulation results using a *QFRESP* value of 0.32 were comparable to those obtained from the SCS-SA model. Furthermore, with the *QFRESP* value fixed at a value of 1 and changing only the *SMDDEP*, the *SMDDEP* had to be reduced to unrealistic values and even then the simulation results were not reduced enough to be comparable to those obtained from the SCS-SA model.

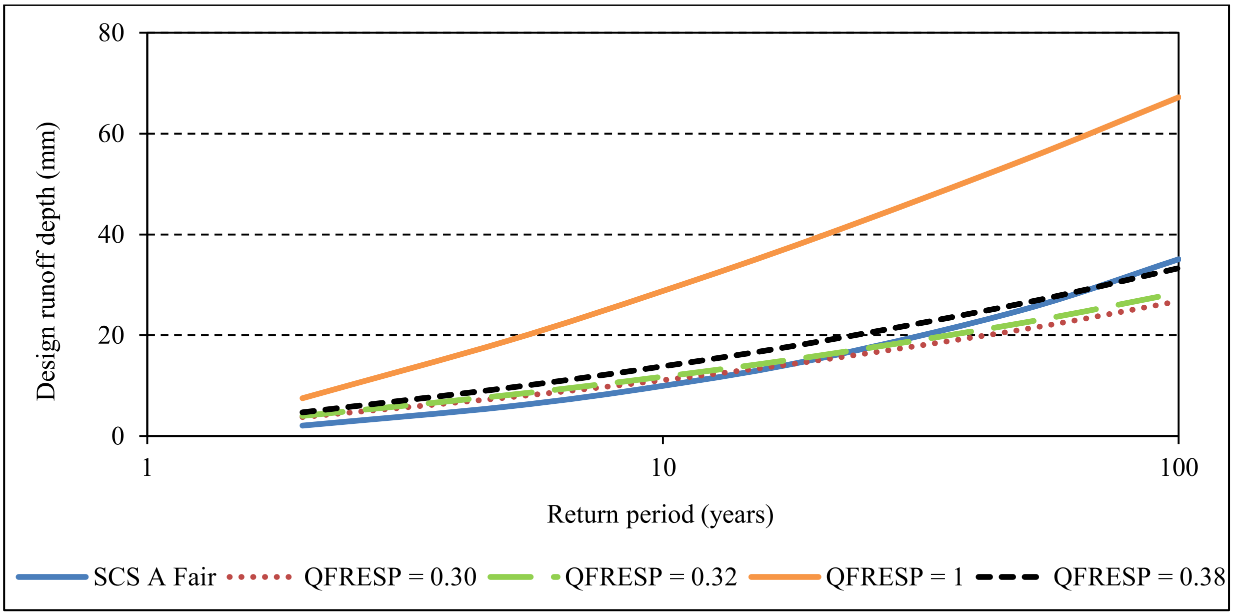


Figure 7.1 SCS-SA and *ACRU* design runoff comparison for a veld in fair condition and a SCS-SA A soil group, Quinary 4854, KZN

Figure 7.2 compares the SCS-SA simulation results for a veld in fair condition and a SCS-SA A/B soil group to those of the *ACRU* model for a similar veld/grassland land cover with adjustment to both the *QFRESP* and *SMDDEP* values to independently assess their impacts.

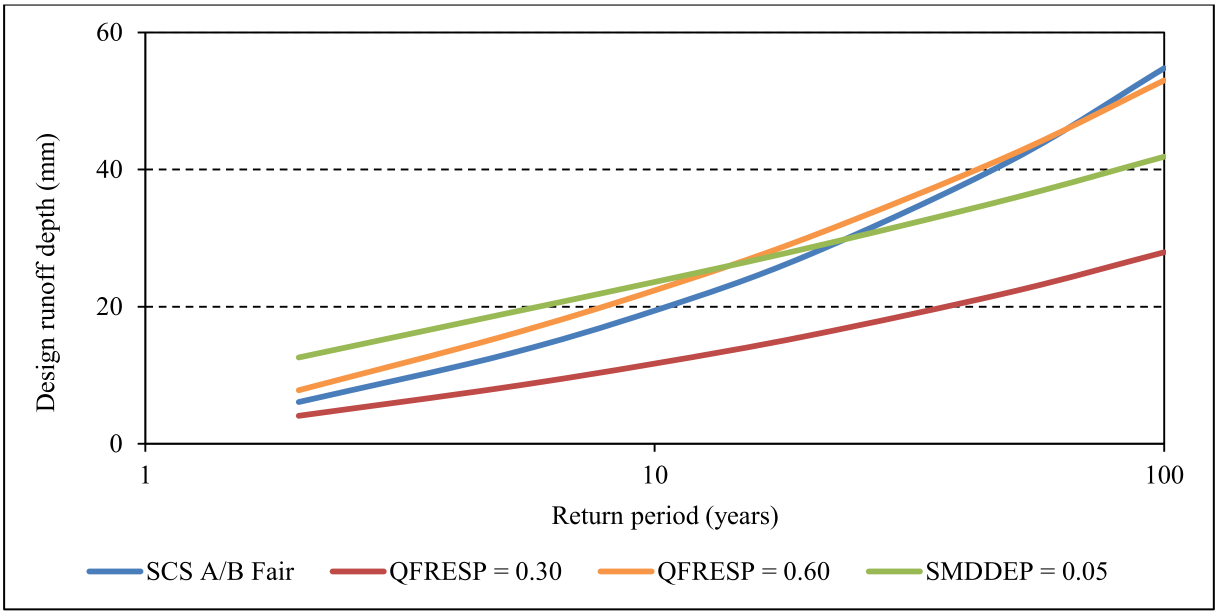


Figure 7.2 SCS-SA and *ACRU* design runoff comparison for a veld in fair condition and a SCS-SA A/B soil group, Quinary 4854, KZN

In this case it is seen that using the default *QFRESP* value of 0.30 does not produce simulation results similar to the SCS-SA model, however, adjusting the *QFRESP* variable to 0.60 significantly improves the similarity between the *ACRU* and SCS-SA simulations. The impact of adjusting *SMDDEP*, instead of *QFRESP*, was also investigated as depicted in Figure 7.2. In this case only *SMDDEP* was adjusted and *QFRESP* was left at the default value of 0.30. The results show that *SMDDEP* has to be adjusted significantly, *i.e.* from a value of 0.25 m (applying the general rule to default *SMDDEP* to the depth of the A horizon) to a value of 0.05, to produce simulation results similar to the SCS-SA model. It is also evident that changing *SMDDEP* has a linear influence on the design runoff depths computed for low as well as high return period events (Figure 7.2). For example, adjusting *SMDDEP* to 0.05 results in an approximately constant increase in the design runoff volumes relative to the simulation results for *QFRESP* = 0.30 for all return period events, *i.e.* from the 2 to 100 year return period. This scenario, however, is not ideal since it results in the over-simulation of low return period events and the under-simulation of high return period events (Figure 7.2). Alternatively, changing *QFRESP* has more of an exponential effect, *e.g.* where a change in *QFRESP* results in small changes in the design runoff volumes for low return period events and larger changes in design runoff volumes for the higher return period events. This scenario is positive as it produces *ACRU* simulation results similar to the SCS-SA simulation results. Therefore, from the analysis of these results and further investigation with other soil groups, it was identified that *QFRESP* is the preferred variable that should be adjusted to represent SCS-SA soil groups in *ACRU*. This, however, is not to say that *SMDDEP* should not be used as it may need to be adjusted jointly with *QFRESP* when *QFRESP* reaches one (1) and cannot be increased any further. Such a scenario is encountered in the analyses to follow for the soil group with the highest runoff potential, SCS-SA soil group D (Figure 7.7).

The simulation results for SCS-SA soil groups B to C/D and calibrated *QFRESP* values are shown in Figure 7.3 to Figure 7.6. For SCS-SA soil group D, the *SMDDEP* value was also adjusted with results shown in Figure 7.7. The results indicate that there is a general increase in the calibrated *QFRESP* value for SCS-SA soil groups, changing from group A to D. This is logical since each progressive increase in SCS-SA soil response group results in a higher runoff response. Therefore, in order to mimic this trend in *ACRU,* the *QFRESP* value must also logically increase when representing each change in SCS-SA soil group, *i.e.* since a higher *QFRESP* value results in higher flood volumes per day and therefore higher design flood estimates.

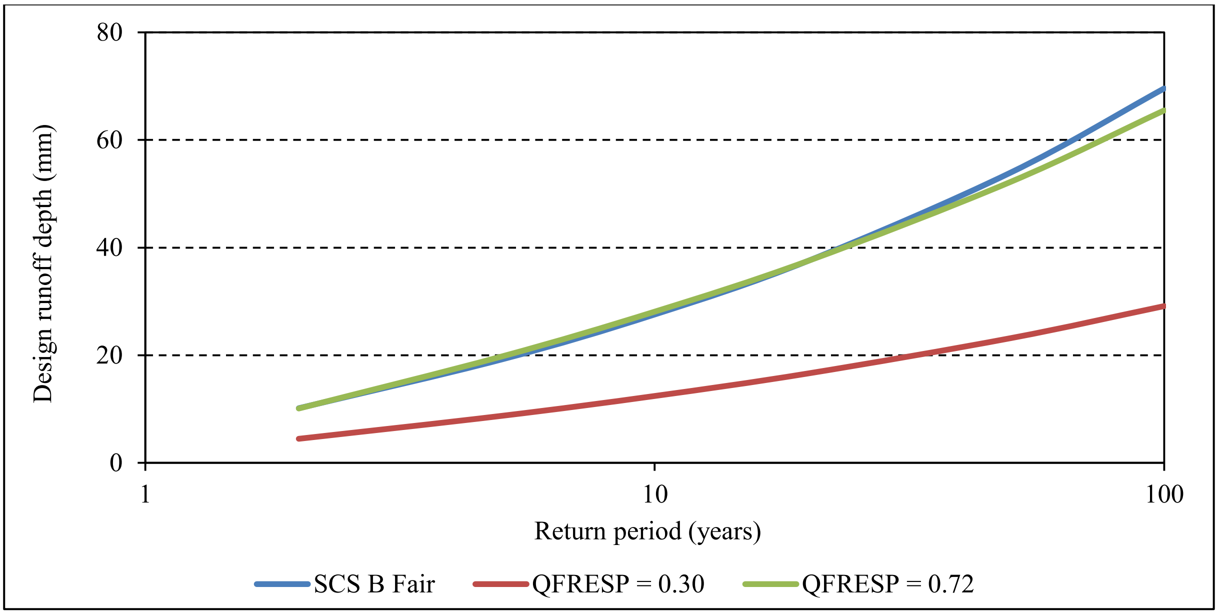


Figure 7.3 SCS-SA and *ACRU* design runoff comparison for a veld in fair condition and a SCS-SA B soil group, Quinary 4854, KZN

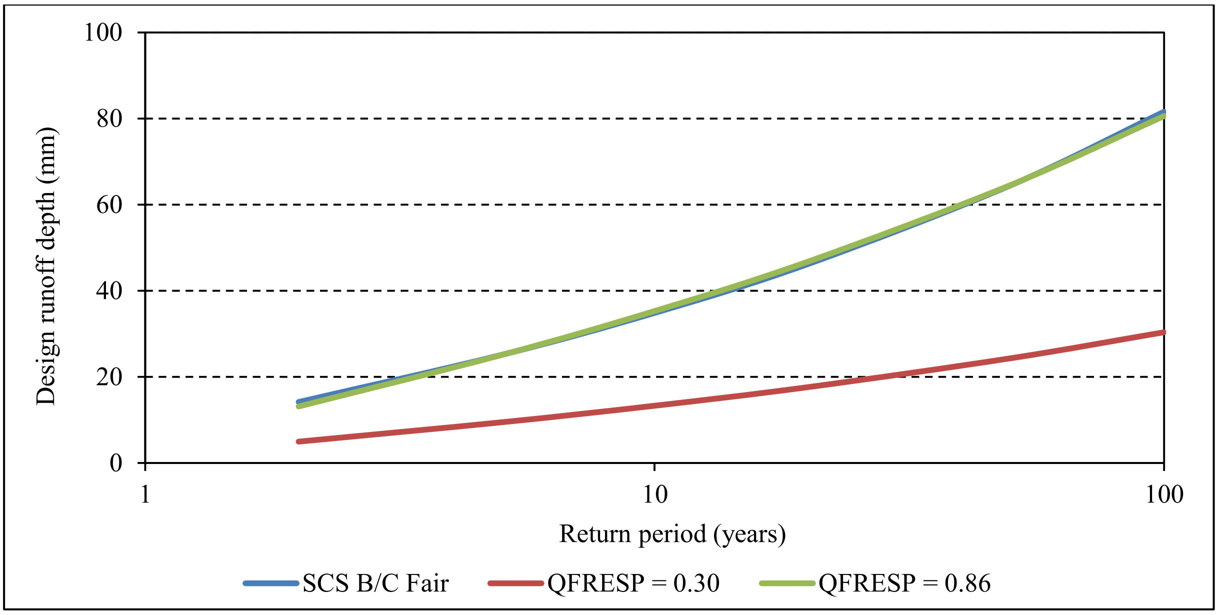


Figure 7.4 SCS-SA and *ACRU* design runoff comparison for a veld in fair condition and a SCS-SA B/C soil group, Quinary 4854, KZN

There is a slight deviation from this trend, however, for SCS-SA soil groups C (Figure 7.5) and C/D (Figure 7.6), where the calibrated *QFRESP* value for SCS-SA soil group C (0.92) is slightly higher than that for SCS-SA soil group C/D (0.90). This anomaly, however, can be explained by referring to Chapter 5.2 and Table 5.5, where the percentage weighted soil textural properties, used in this analysis, were determined through the Binomial approach. Recalling from Table 5.5 that the PWP increases significantly going from a SCS-SA C soil group (0.153) to a SCS-SA C/D soil group (0.209), with the PO remaining relatively similar between the two, it is evident that the soil water storage capacity of a SCS-SA C/D soil is considerably smaller than that of a SCS-SA C soil. This results in a noticeably higher runoff response for a SCS-SA C/D soil compared to a SCS-SA C soil. Therefore, in term of the adjustment to *QFRESP* to represent SCS-SA C and C/D soils, it is clear that the *QFRESP* value for a SCS-SA C/D soil does not need to be larger than that for a SCS-SA C soil, since the soil textural properties derived for a SCS-SA C/D soil are significantly different from those of a SCS-SA C soil, as well as a SCS-SA D soil for that fact. The difference is large enough that it alone accounts for the difference in runoff response between a SCS-SA C and C/D soil and therefore the calibrated *QFRESP* values are very similar. Furthermore, as mentioned in Section 5.2, the soil textural properties for a SCS-SA C/D soil were identified as anomalous to the general trends identified between soil groups. Therefore, it is no surprise that the anomaly identified within Section 5.2 would be directly translated into the results from this analysis. Through calibration, however, the anomalous trend is overcome and accounted for.

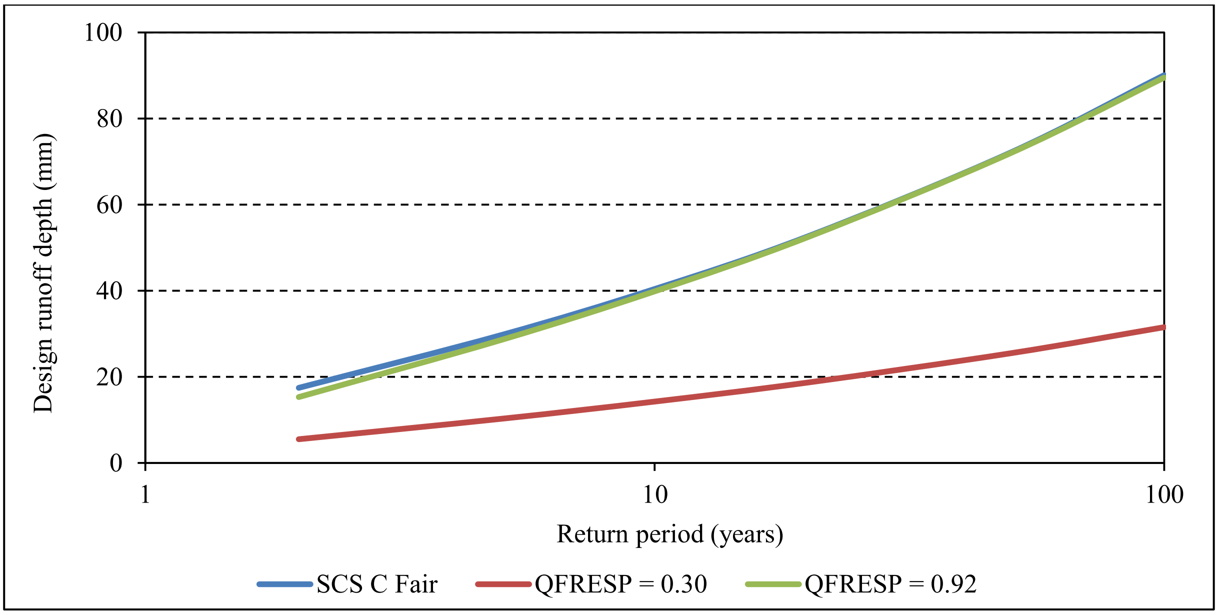


Figure 7.5 SCS-SA and *ACRU* design runoff comparison for a veld in fair condition and a SCS-SA C soil group, Quinary 4854, KZN

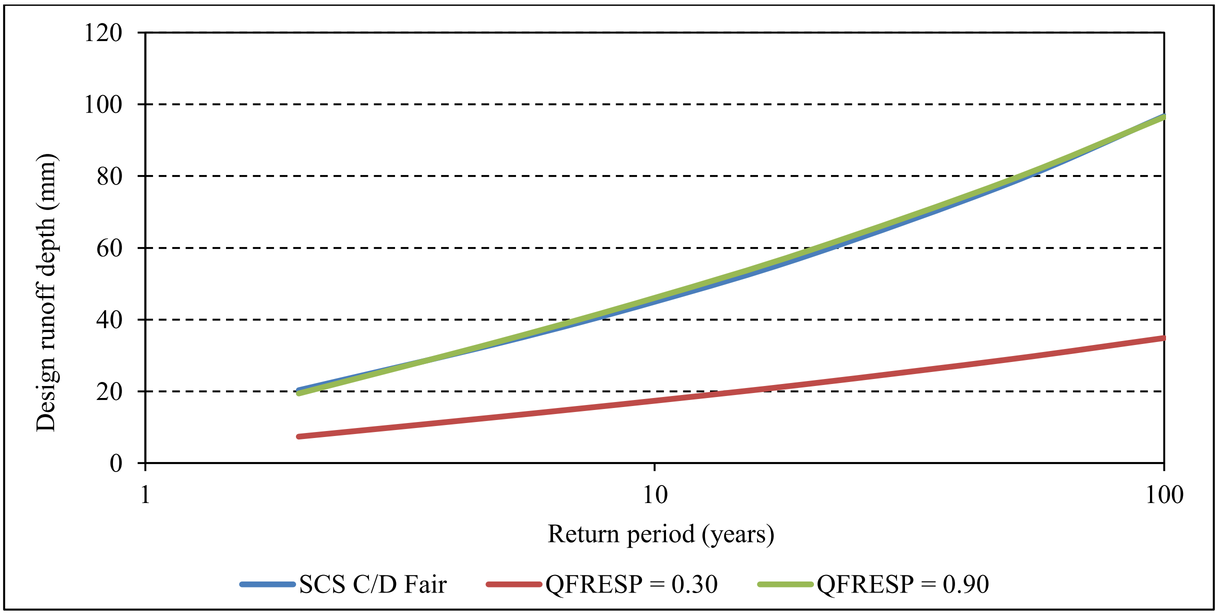


Figure 7.6 SCS-SA and *ACRU* design runoff comparison for a veld in fair condition and a SCS-SA C/D soil group, Quinary 4854, KZN

As mentioned previously, Figure 7.7 shows how *QFRESP*, as well as *SMDDEP*, were adjusted to achieve comparable simulation results between the SCS-SA and *ACRU* models for a SCS-SA D soil group. Initially the *QFRESP* was set to one and the *ACRU* simulation was similar to the SCS-SA simulation for a SCS-SA D soil group, however, additional adjustment of the *SMDDEP* variable to 0.20m (from the default value of 0.25m) improved the simulation similarity even further and therefore *SMDDEP* was also adjusted jointly with *QFRESP*.

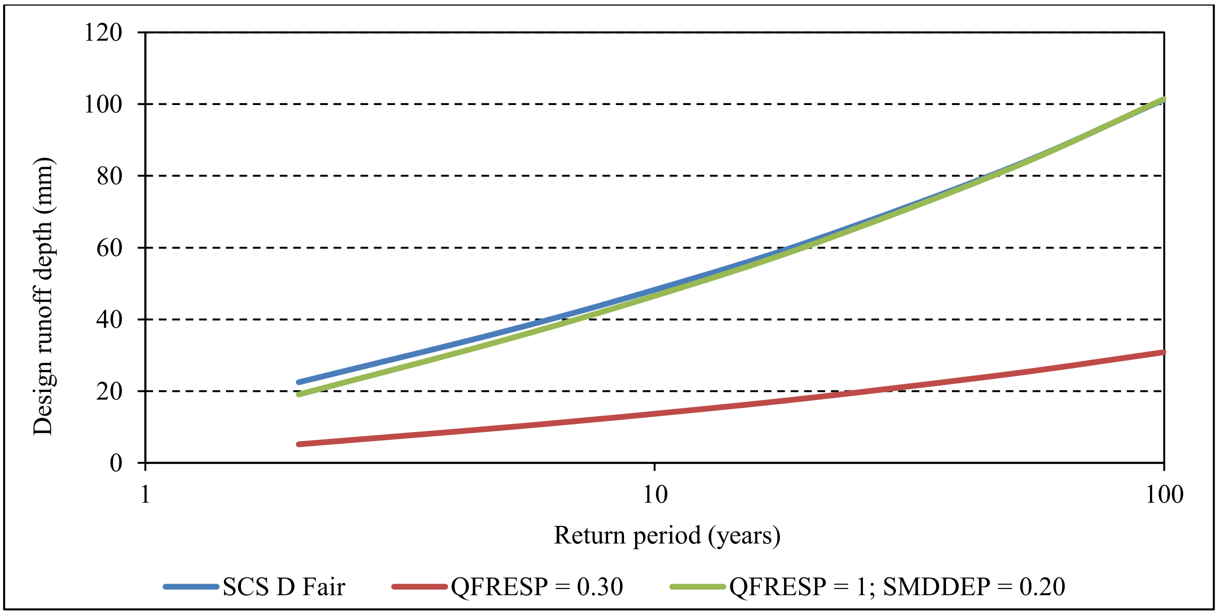


Figure 7.7 SCS-SA and *ACRU* design runoff comparison for a veld in fair condition and a SCS-SA D soil group, Quinary 4854, KZN

In summary, the calibration results using *QFRESP* and *SMDDEP* to represent SCS-SA soil groups for a veld/grassland land cover in fair condition were very promising and produced highly comparable results. Therefore, further investigation for a veld in poor condition and a veld in good condition was undertaken. The following section contains the results for a veld in poor condition.

7.1.2 Veld/Grassland land cover in poor condition

This section contains the comparison of the simulation results between the SCS-SA model and the *ACRU* model for a veld/grassland land cover in poor condition. Similar to the approach in the previous chapter, the *QFRESP* and *SMDDEP* variables are used to represent each of the SCS-SA soil groups for a veld in poor hydrological condition. Even though design flood estimates using the *ACRU* model have been shown to be insensitive to the vegetation related variables (*VEGINT, CAY, COIAM* and *PCSUCO*), these are adjusted to account for land cover condition as recommended by Schulze (2013). Schulze (2013) developed rules for the simulation of degraded areas, with the assumption that the degradation is severe. The information contained within the QCD for natural vegetation was set as the point of departure for assigning altered hydrological attributes to degraded areas (Schulze, 2013). The *ACRU* parameters to be changed for the simulation of runoff from degraded areas include the following monthly parameters (Schulze, 2013):

(i) *CAY*, reduced by a factor of 1.4 in all months, but with the provision that *CAY* values not allowed to drop below 0.2 in any month;
(ii) *VEGINT*, reduced by 50% in all months;
(iii) *COIAM*, reduced to 0.10 for the months November to March, 0.15 for April, May and October and 0.20 for months June to September, while in the winter / all year rainfall areas *COIAM* values would be reduced from the conventional 0.30 for each month to 0.20; and
(iv) *PCSUCO*, reduced to 10% for all months of the year.

Figure 7.8 compares the simulation results from the SCS-SA model for a veld in poor condition and a SCS-SA A soil group with the simulation results from the *ACRU* model for: (i) a veld in fair condition and the calibrated *QFRESP* value (0.32) determined in the previous section (Fair_*QFRESP* = 0.32); (ii) a veld in poor condition using the same *QFRESP* (0.32), however, changing the *VEGINT, CAY, COIAM* and *PCSUCO* variables as suggested by Schulze (2013) (Poor_*QFRESP* = 0.32); and (iii) a veld in poor condition again changing the *VEGINT, CAY, COIAM* and *PCSUCO* variables as suggested by Schulze (2013), with calibration of the *QFRESP* variable until the *ACRU* simulation results were similar to the SCS-SA results (Poor_*QFRESP* = 0.70). From the results (Figure 7.8), it is again highlighted that in terms of design flood estimates the *ACRU* model is insensitive to changes in *VEGINT, CAY, COIAM* and *PCSUCO*. This is identified through the very small differences in runoff responses between simulation results Fair_*QFRESP* = 0.32 and Poor_*QFRESP* = 0.32. An additional adjustment of the *QFRESP* variable, however, to a value of 0.70 (Poor_*QFRESP* = 0.70) significantly improved the SCS-SA to *ACRU* simulation comparison. Therefore it is clear that in terms of design flood estimates, the adjustments suggested by Schulze (2013) have a negligible influence on the simulated design runoff volumes.

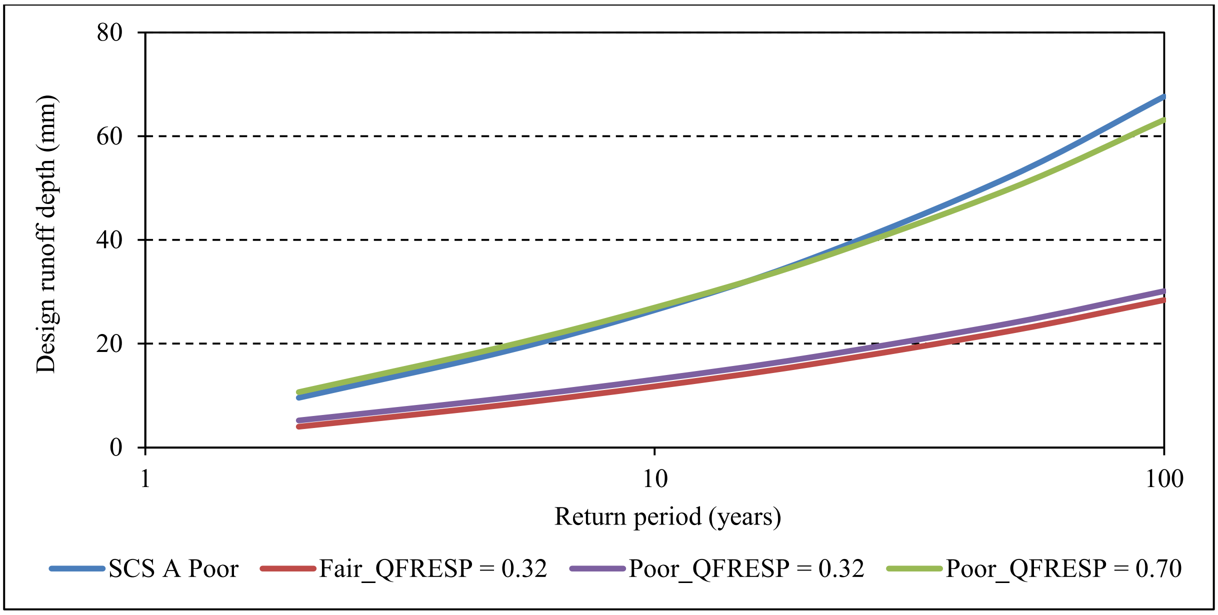


Figure 7.8 SCS-SA and *ACRU* design runoff comparison for a veld in poor condition and a SCS-SA A soil group, Quinary 4854, KZN

Figure 7.9 compares the simulation results from the SCS-SA model for a veld in poor condition and SCS-SA soil groups A/B to D with the calibrated simulation results from the *ACRU* model. For each of the *ACRU* simulations depicted in Figure 7.9, the *VEGINT, CAY, COIAM* and *PCSUCO* variables were once again changed by applying the rules developed by Schulze (2013) and then, through calibration, adjustments were made to the *QFRESP* and *SMDDEP* variables until the *ACRU* simulation results closely matched the SCS-SA simulation results. In terms of the adjustment to the *QFRESP* and *SMDDEP* variables, a general rule was developed that *SMDDEP* should only be adjusted after the *QFRESP* variable has been set to a value of 1, *i.e.* the *QFRESP* variable should be adjusted first and if it reaches a value of one and the *ACRU* and SCS-SA simulation results are still not similar, then subsequent adjustment of the *SMDDEP* variable should be performed. The results (Figure 7.9) once again show that similar simulation results are obtained when calibrating *QFRESP* and *SMDDEP* variables to represent SCS-SA soil groups for a veld/grassland land cover in poor hydrological condition. Having reviewed the simulation results for a veld in poor condition the next step, as outlined above, is to analyse the simulation results for a veld in good condition. The following section therefore examines the results for a veld in good condition.

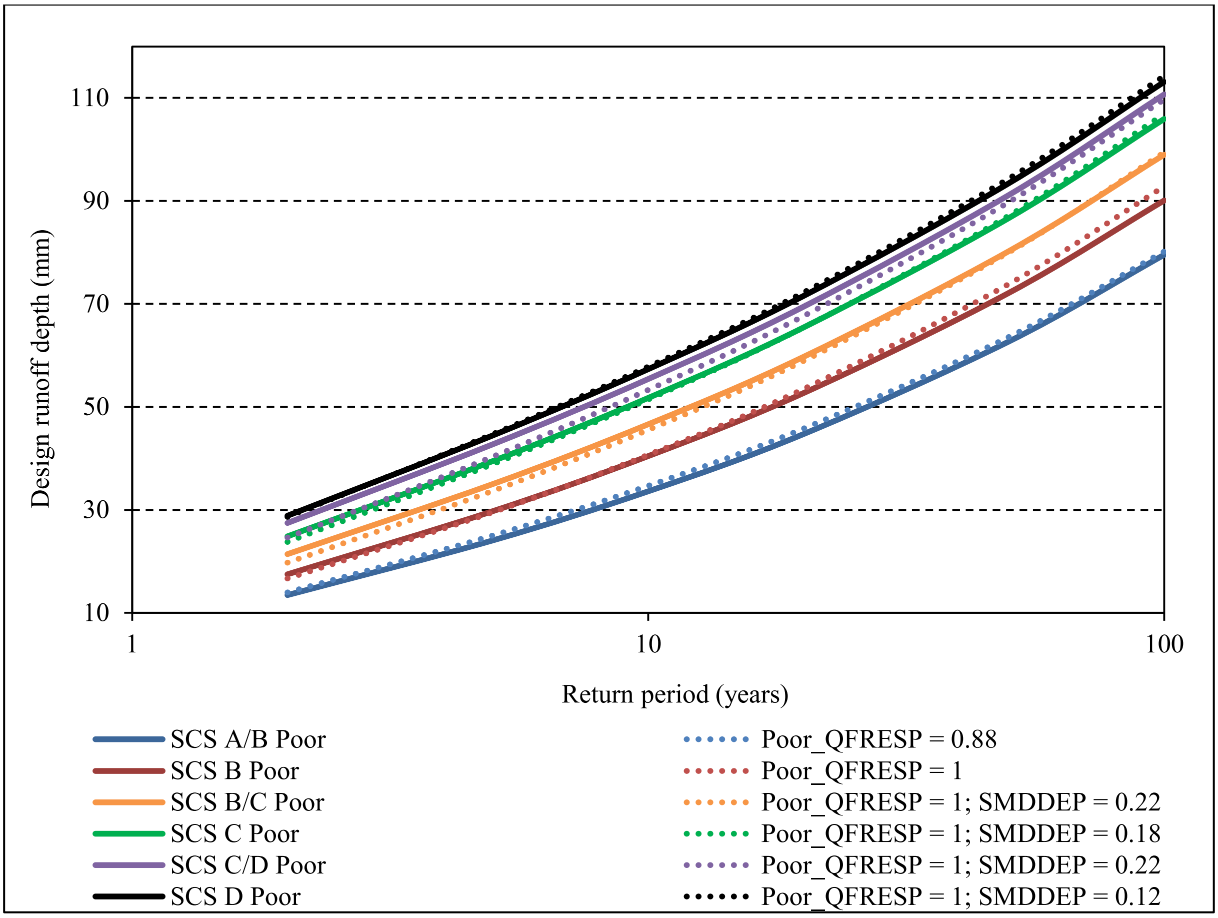


Figure 7.9 SCS-SA and *ACRU* design runoff comparisons for a veld in poor condition and SCS-SA soil groups A/B to D for Quinary 4854, KZN

7.1.3 Veld/Grassland land cover in good condition

This section contains the comparison of the simulation results between the SCS-SA model and the *ACRU* model for a veld/grassland land cover in good condition. Similar to the approach in the previous section, the *QFRESP* and *SMDDEP* variables were again used to represent each of the SCS-SA soil groups, however, for a veld in good hydrological condition. In addition, alteration to the *VEGINT* and *CAY* variables were also undertaken, since once again this has been identified to be conceptually and hydrologically correct even though the model is insensitive to these variables in terms of design flood estimates. Unlike in the previous section, where rules developed by Schulze (2013) were available to represent a veld/grassland in poor hydrological condition, in this case new rules had to be generated to represent a veld in good hydrological condition, assuming that the standard values within the QCD are representative of a veld in fair condition. As stated previously, it was decided that only the *VEGINT* and *CAY* variables should be adjusted to represent a veld in good hydrological condition and not the *COIAM* and *PCSUCO* as in the previous chapter for a veld in poor condition. The rationale for this is based on the following: (i) in Chapter 6, it was highlighted that in the *ACRU* model the *COIAM* accounts for the following: land use/land cover, vegetation characteristics, *i.e.* development stage, rainfall seasonality and rainfall intensity (Topping, 1992) and since this variable already accounts for several other properties it was considered preferable to avoid using this variable; (ii) in terms of the *PCSUCO* variable, there is conflict between the model processes and what is conceptually correct and this can lead to erroneous or misleading results. For example, if the *PCSUCO* variable is increased, conceptually it is assumed that there would be less soil water evaporation, *i.e.* through suppression from a greater mulch/surface cover, which is accounted for in the model. In addition, however, the increased surface cover would intercept more rainfall and increase the retardance to surface runoff. The latter, however, is poorly represented in the model because increasing *PCSUCO* does not change the amount of rainfall intercepted and it does not account for the reduction in runoff due to increased retardance. The model simulates an increase in surface runoff since the soil remains wetter due to the increased suppression of soil water evaporation. Consequently, the hydrological processes associated with the *PCSUCO* variable are poorly represented in the *ACRU* model. Procedures to better represent the *PCSUCO* variable in the *ACRU* model are therefore recommended in future research. It was therefore decided that the *PCSUCO* variable should not be adjusted to represent a veld in good condition. The following rules were derived for the simulation of veld in good condition:

(i) *CAY* was increased, *i.e.* from the standard values for a veld in fair condition, by a factor of 1.2 for all months; and
(ii) *VEGINT* was increased by 25% for all months.

In addition to these adjustments, which have a negligible influence on the design runoff volumes simulated, the *QFRESP* and *SMDDEP* variables were adjusted, again through calibration, in order to obtain *ACRU* simulation results which mimic the results from the SCS-SA model. Figure 7.10 compares the average absolute differences between SCS-SA and *ACRU* design runoff volumes (averaged for all return periods from 2 – 100 years) for each SCS-SA soil group A to D for a veld in fair, poor and good condition. The results (Figure 7.10) show that in all cases the average absolute differences between the SCS-SA and *ACRU* design runoff volumes are small and are all less than 3mm. Therefore in terms of the rules developed to quantify the significance of the comparisons, the results are all comparable with a large majority of the results being highly comparable. Furthermore, the results (Figure 7.10) are a major improvement on the results obtained from the Land Type, Binomial and Calibration approaches (Figure 5.13). These results further support the findings presented above that highly comparable results and trends between the SCS-SA and *ACRU* models can be achieved when calibrating the *QFRESP* and *SMDDEP* variables in the *ACRU* model to represent SCS-SA soil groups. In general, the comparisons were most similar for a veld in poor condition, followed by a veld in fair condition, however, this was not always the case for all SCS-SA soil groups (Figure 7.10). The differences are attributed to the calibration procedure where values were manually calibrated, resulting in scenarios where some calibrations were optimised better than others. Ultimately, however, although there are slight differences between the results, overall the results show that comparable and highly comparable results were obtained for all the veld land cover classes investigated through the calibration procedure.

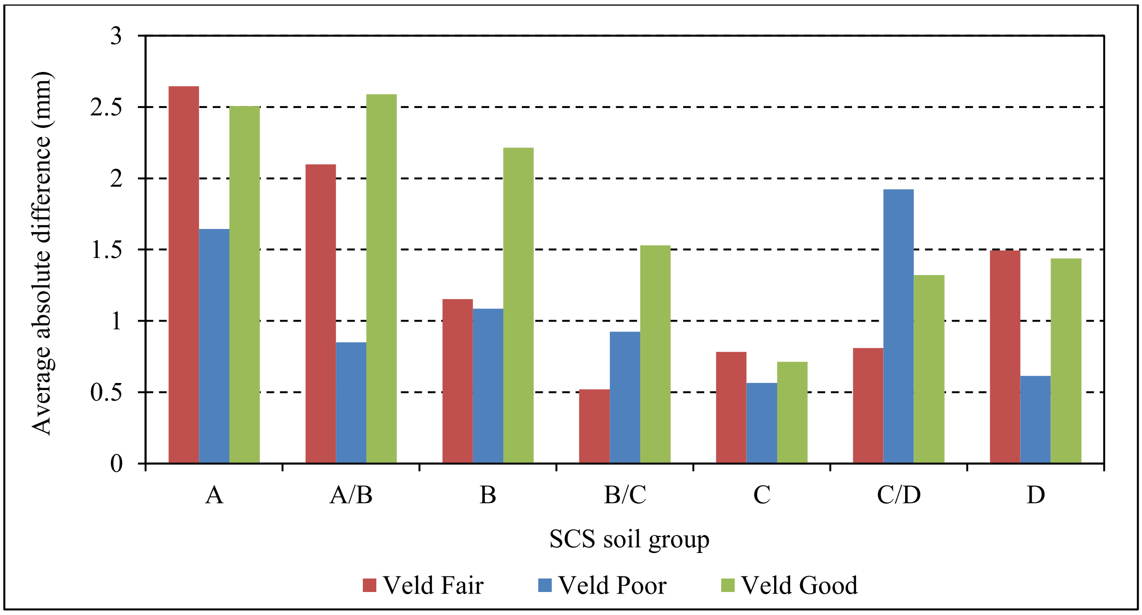


Figure 7.10 Average absolute difference between SCS-SA and *ACRU* design runoff simulations (averaged for the 2 – 100 year return periods) for a veld in fair, good and poor condition in KZN for SCS-SA soil groups A to D

Very promising results have been presented in the previous three sections, showing that the *QFRESP* and *SMDDEP* variables may be used to represent SCS-SA soil groups/CNs for a veld/grassland land cover in fair, good and poor condition. The investigation, however, needs to be extended to different land cover classes such as maize and sugarcane. Maize and sugarcane were selected since these are two major crops cultivated in South Africa, particularly in the eastern parts of the country. The following section therefore analyses the results for a maize/row crop land cover.

7.1.4 Row Crop/Maize land cover

In the SCS-SA land cover classification, there are several different classes within the general row crop land cover class, for different land management practices and stormflow potentials/hydrological conditions (Table 3.1). The same approach applied in the previous section for a veld/grassland land cover was used in this analysis for a maize/row crop land cover, *i.e.* calibrating *QFRESP* and *SMDDEP* values to represent each of the SCS-SA row crop classes and soil groups within each class. The default *ACRU* model input values for a general maize crop planted in November, in all feasible locations within South Africa (COMPOVEG crop number 3120102), was used to represent a row crop/maize land cover in good hydrological condition, *i.e.* a low stormflow potential.

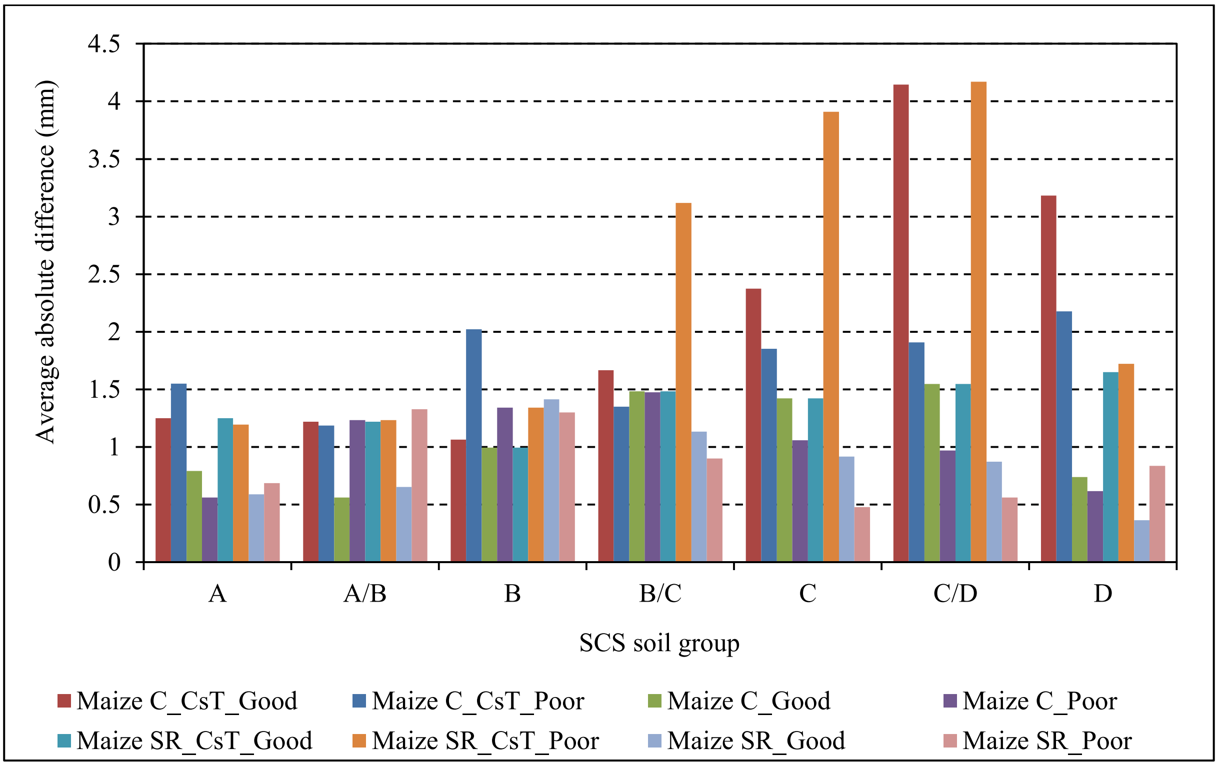
To represent a row crop/maize land cover in poor hydrological condition, the *CAY* and *VEGINT* variables were adjusted from the defaults as follows:

(i) *CAY* was reduced by 10%, but with the provision that *CAY* values are not allowed to drop below 0.2 in any month; and
(ii) *VEGINT* was reduced by 20% in all months.

Once again these adjustments alone result in negligible differences in runoff responses, however, they have been altered because conceptually these variables would be influenced by hydrological condition. Management practice, hydrological condition and SCS-SA soil groups were then represented in *ACRU* through calibration of the *QFRESP* and *SMDDEP* variables.

Figure 7.11 summarises and compares the results for the various maize land cover classes investigated. The average absolute differences between SCS-SA and *ACRU* design runoff volumes (averaged for all return periods from 2 – 100 years) are depicted for each SCS-SA soil group A to D for the various maize land cover classes investigated. The results (Figure

7.11) show that in all cases the average absolute differences between the SCS-SA and *ACRU* design runoff volumes are small and are generally less than 2mm, *i.e.* highly comparable, with a few exceptions where averages are greater than 2mm but less than 6mm, *i.e.* comparable. Although there are slight differences between the results, overall the results show that comparable and highly comparable results were once again obtained for all the maize land cover classes investigated through calibration.



*C_CsT_Good: Planted on the contour, with conservation tillage, in good condition; C_CsT_Poor: Planted on the contour, with conservation tillage, in poor condition; C_Good: Planted on the contour, in good condition; C_Poor: Planted on the contour, in poor condition; SR_CsT_Good: Planted in straight rows, with conservation tillage, in good condition; SR_CsT_Poor: Planted in straight rows, with conservation tillage, in poor condition; SR_Good: Planted in straight rows, in good condition; SR_Poor: Planted in straight rows, in poor condition.

Figure 7.11 Average absolute difference between SCS-SA and *ACRU* design runoff simulations (averaged for the 2 – 100 year return periods) for various maize land cover classes in KZN for SCS-SA soil groups A to D

Another crop that is commonly cultivated in the eastern parts of South Africa is sugarcane. Difficulty comparing the design runoff responses from the *ACRU* and SCS-SA models for a sugarcane land cover was encountered and required aid from statistical analysis of the results obtained previously and some additional results from different geographical locations, *i.e.*

Mpumalanga and the Western Cape. Consequently the sugarcane analyses will be presented later once the Mpumalanga and Western Cape results and statistical analyses have been presented. The following section investigates the consistency of the previous findings for a veld/grassland land cover in a different geographical location with a different climate, *i.e.* Mpumalanga.

7.2 Consistency Testing: Mpumalanga

As stated in the previous section, this chapter aims to investigate if the *QFRESP* and *SMDDEP* values found to represent SCS-SA soil groups for a veld land cover in KZN may be directly transferred and used under different climatic conditions in the Mpumalanga province (Figure 7.12). This has been performed in order to verify that the selection of *QFRESP* and *SMDDEP* variables to represent SCS-SA CNs for different soil groups and hydrological conditions can be transferred and applied at different locations within South Africa.

The approach applied to perform this verification once again involved comparing the design runoff volumes simulated from the SCS-SA model with those from the *ACRU* model. In this case, however, the *QFRESP* and *SMDDEP* values representing each SCS-SA soil group and hydrological condition for a veld/grassland land cover were not estimated through calibration, as in the previous chapter. Rather the *QFRESP* and *SMDDEP* values as determined for a veld/grassland land cover in KZN were used and the results analysed to observe if similar simulation results were again obtained between the SCS-SA and *ACRU* models at another location. It is important to note that a hypothetical catchment area of 1km^2 was once again used in both the SCS-SA and *ACRU* model simulations, however, in this case assuming climatic and physical catchment conditions for a randomly selected quinary catchment in Mpumalanga, Quinary B11A2 (Quinary number – 434, in the QCD), depicted in Figure 7.12.

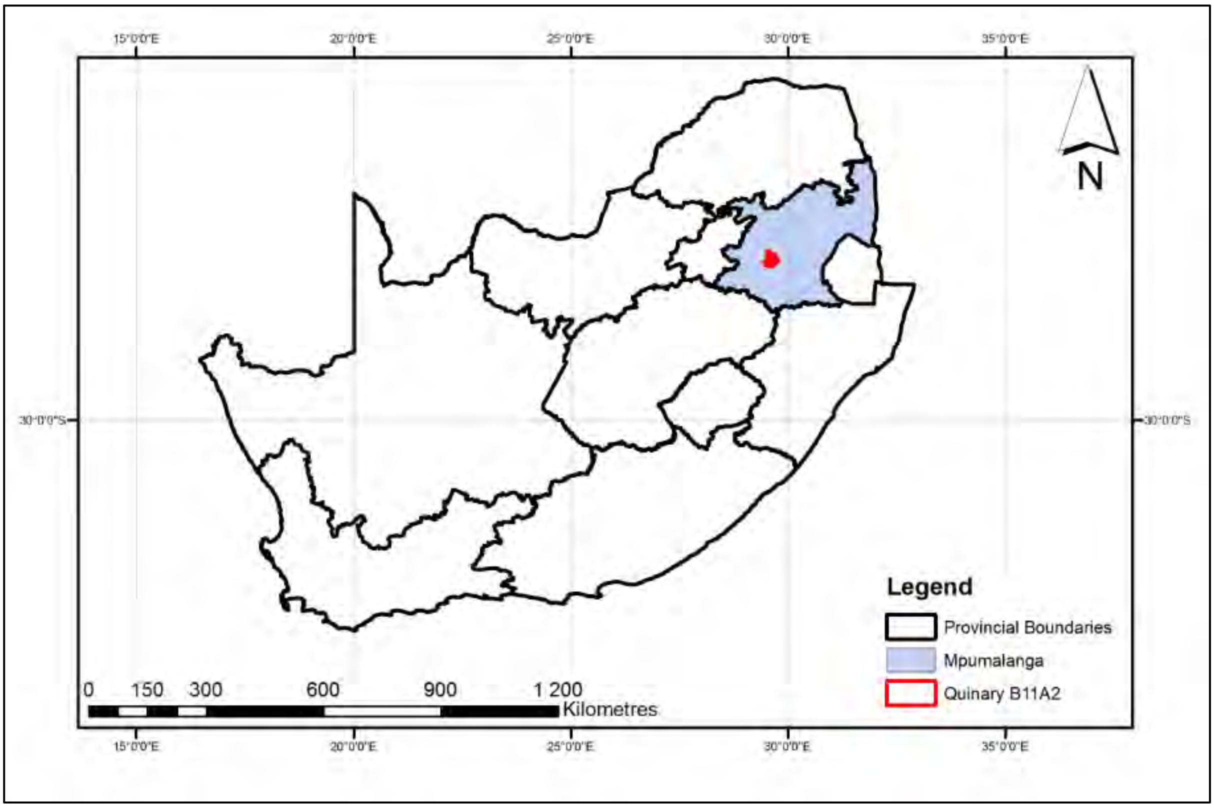


Figure 7.12 Location map of Quinary B11A2 (MAP – 628mm) in Mpumalanga, South Africa

The data from the QCD, with default climate information and other physical attributes for Quinary 434, was used in the simulations. The daily rainfall file assigned to Quinary 434 was used as the input into the *ACRU* model and the same daily rainfall file was used to calculate the design rainfall input values for the SCS-SA model. A veld/grassland land cover in fair hydrological condition was once again investigated first. The model set-up for the SCS-SA model was the same as used in the KZN simulation, however, with a different design rainfall input, *i.e.* as determined by the *ACRU* model from the LP-III extreme value distribution derived from the AMS extracted from the daily rainfall file for Quinary 434, Mpumalanga. Similarly, the same model set-up as used in the KZN simulation was used in the *ACRU* model, however, changing the climate file as well as the land cover to the prevailing natural vegetation found within Quinary B11A2 [Crop Number – 2030318 – Bankenveld (Acocks #61)], as defined in the COMPOVEG database built into the *ACRU* model (Smithers and Schulze, 2004). The COMPOVEG values assigned to the model variables representing the Bankenveld vegetation were used, unchanged, to represent a veld/grassland land cover in fair condition. This is in accordance with the procedure applied in the KZN simulations for a veld in fair condition where the prevailing vegetation properties were also unaltered.

7.2.1 Veld/Grassland land cover in fair condition

Figure 7.13 illustrates the design runoff trends calculated by the SCS-SA model for a Veld land cover, in fair hydrological condition, for SCS-SA soil groups A to D at specific return periods, along with the input design rainfall estimated for Quinary 434, Mpumalanga. Table 7.1 contains a summary of the calibrated *QFRESP* and *SMDDEP* values for SCS-SA soil groups A to D, for a veld land cover in fair condition, within Quinary 4854, KZN, South Africa, as derived in Section 7.1.1.

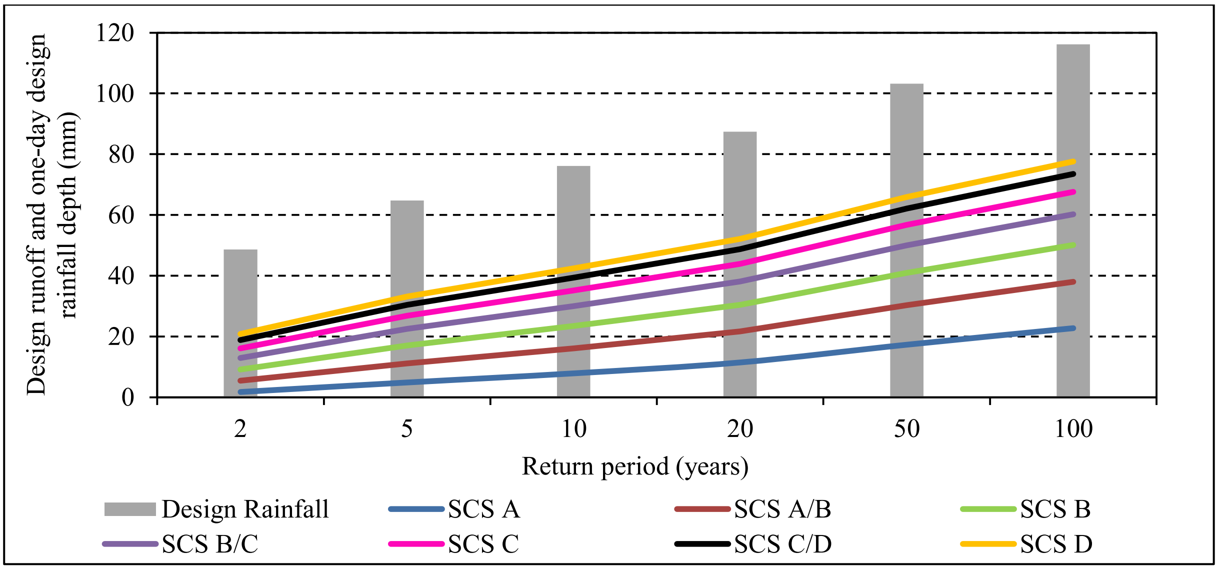


Figure 7.13 SCS-SA hydrological responses computed for a veld land cover, in fair hydrological condition, for soil groups A – D at specific return periods and the causative design rainfall, Quinary 434, Mpumalanga

Table 7.1 Calibrated *QFRESP* and *SMDDEP* values found to represent SCS-SA soil groups A to D for a veld land cover in fair condition, KZN

SCS-SA Soil Group	**Calibrated *QFRESP* and *SMDDEP* Values**
A soil	*QFRESP* = 0.32
A/B soil	*QFRESP* = 0.60
B soil	*QFRESP* = 0.72
B/C soil	*QFRESP* = 0.86
C soil	*QFRESP* = 0.92
C/D soil	*QFRESP* = 0.90
D soil	*QFRESP* = 1 *SMDDEP* = 0.20

Figure 7.14 compares the simulation results between the *ACRU* and SCS-SA models for SCS-SA soil groups A to D, where the *QFRESP* and *SMDDEP* values from Table 7.1 were used to produce the *ACRU* simulation results corresponding to each SCS-SA soil group. The results show that there is high correlation between the SCS-SA and *ACRU* model results, when applying the calibrated *QFRESP* and *SMDDEP* values from Quinary 4854, KZN (Table 7.1). The similarity between SCS-SA and *ACRU* simulation results (Figure 7.14), however, are generally not as significant as they were for Quinary 4854 in KZN (Figure 7.1 - Figure 7.7). This is highlighted in Figure 7.15 where the average absolute differences between SCS-SA and *ACRU* design runoff volumes (averaged for all return periods from 2 – 100 years) for each SCS-SA soil group A to D have been plotted, for both the Mpumalanga and KZN simulations. The results (Figure 7.15) show that for SCS-SA soil groups A and A/B, the average absolute difference between SCS-SA and *ACRU* design runoff volumes is actually slightly lower for the Mpumalanga simulations compared to the KZN simulations, with the results being highly comparable. For soil groups B to D, however, the average differences are noticeably higher for the Mpumalanga province when compared to the KZN province. The results are still comparable, however they are not highly comparable as they were for the KZN simulations. This trend, however, is to be expected since each simulation comparison for Quinary 4854 in KZN was optimised individually, through calibration. The simulation results depicted in Figure 7.14 are nonetheless still comparable, whilst importantly still maintaining the desired trend of increasing runoff from an "*ACRU* A soil group" (Fair_*QFRESP* = 0.32) to an "*ACRU* D soil group" (Fair_*QFRESP* = 1; *SMDDEP* = 0.20).

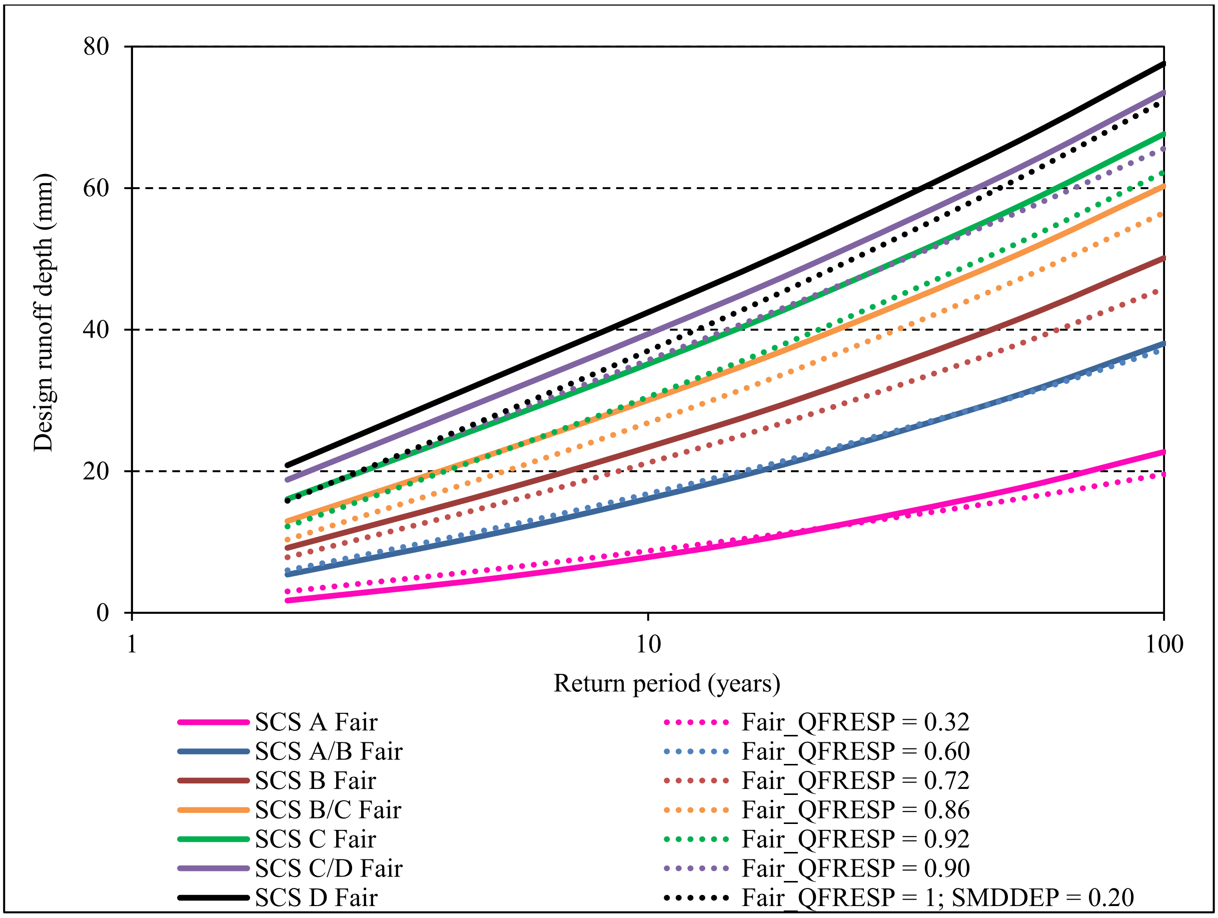


Figure 7.14 SCS-SA and *ACRU* design runoff comparisons for a veld in fair condition and SCS-SA soil groups A to D for Quinary 434, Mpumalanga

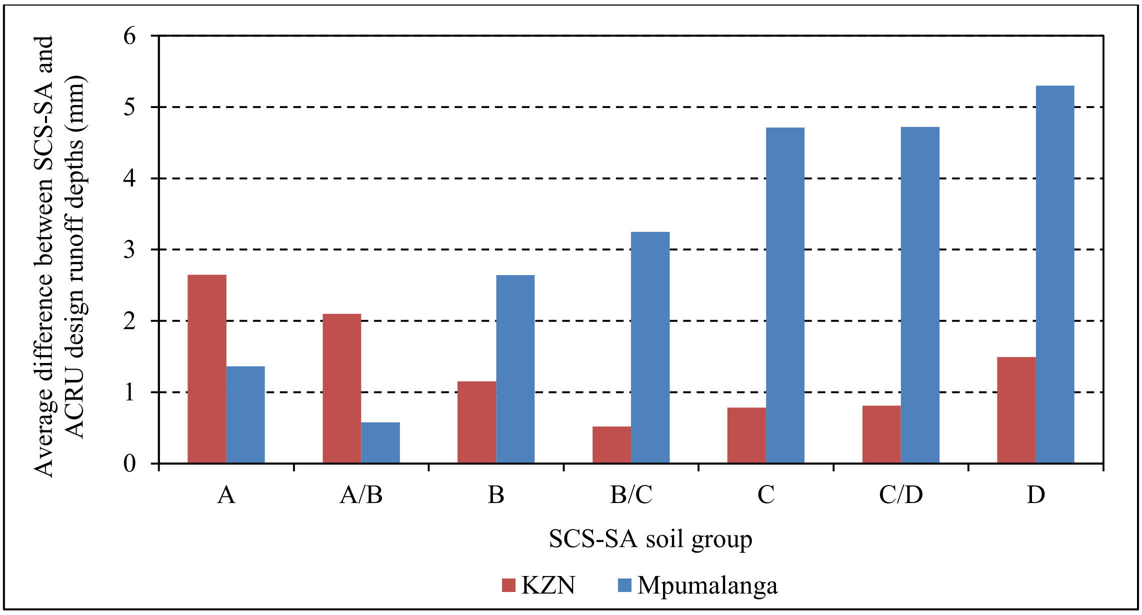


Figure 7.15 Average absolute difference between SCS-SA and *ACRU* design runoff simulations (averaged for the 2 – 100 year return periods) for a veld land cover in good condition in the KZN and Mpumalanga provinces for SCS-SA soil groups A to D

Analysis of the results for a veld land cover in fair hydrological condition, within the Mpumalanga province, are positive and indicate that the rules developed to represent SCS-SA soil groups in *ACRU* are capable of reproducing consistent results in a different geographical location in South Africa. The next section presents the results from applying the rules developed thus far for a veld land cover in poor hydrological condition.

7.2.2 Veld/Grassland land cover in poor condition

In this section, the design runoff volumes simulated by the SCS-SA and *ACRU* models are compared for a veld land cover in poor hydrological condition, within Quinary 434, Mpumalanga. In terms of the SCS-SA model set-up, the same set-up as used previously for a veld in fair hydrological condition was used, however, changing the CNs to those representative of a veld in poor hydrological condition. Similarly the *ACRU* model set-up remained the same as previously for a veld in fair condition, however, again adjusting several of the input variables as suggested by Schulze (2013) to represent a veld in poor condition. The adjustments made to represent a veld in poor condition are identical to those used in the KZN simulations (Chapter 7.1.2).

The *QFRESP* and *SMDDEP* values (Table 7.2) calibrated to represent a veld in poor condition from the KZN simulations, were used directly in the *ACRU* simulations to represent each of the respective SCS-SA soil groups. Figure 7.16 compares the simulation results between the *ACRU* and SCS-SA models for SCS-SA soil groups A to D.

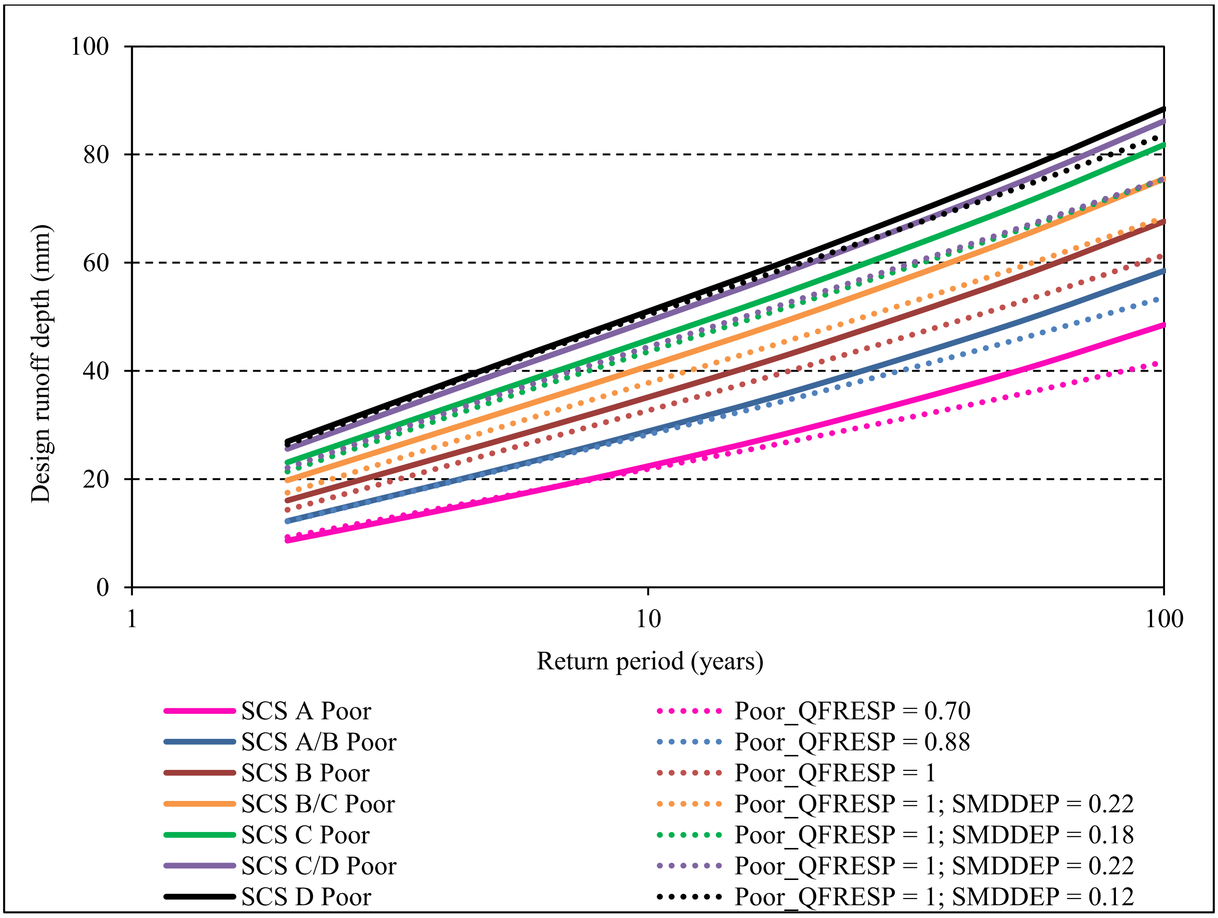


Figure 7.16 SCS-SA and *ACRU* design runoff comparisons for a veld in poor condition and SCS-SA soil groups A to D for Quinary 434, Mpumalanga

Table 7.2 Calibrated *QFRESP* and *SMDDEP* values found to represent SCS-SA soil groups A to D for a veld in poor condition, KZN

SCS-SA soil group	**Calibrated *QFRESP* and *SMDDEP* values**
A soil	*QFRESP* = 0.70
A/B soil	*QFRESP* = 0.88
B soil	*QFRESP* = 1
B/C soil	*QFRESP* = 1 *SMDDEP* = 0.22
C soil	*QFRESP* = 1 *SMDDEP* = 0.18
C/D soil	*QFRESP* = 1 *SMDDEP* = 0.22
D soil	*QFRESP* = 1 *SMDDEP* = 0.12

The results presented in Figure 7.16 show that there is high correlation between the SCS-SA and *ACRU* model results, when applying the calibrated *QFRESP* and *SMDDEP* values from Quinary 4854, KZN (Table 7.2). The similarity between SCS-SA and *ACRU* simulation results depicted in Figure 7.16, however, are not as significant as they were for Quinary 4854 in KZN (Figure 7.8 and Figure 7.9). This is highlighted in Figure 7.17 where the average absolute differences between SCS-SA and *ACRU* design runoff volumes for each SCS-SA soil group A to D have been plotted, for both the Mpumalanga and KZN simulations. The results show that for SCS-SA soil groups A to D, the average absolute differences between SCS-SA and *ACRU* design runoff volumes is consistently higher for the Mpumalanga province when compared to the KZN province. In terms of the KZN simulations, highly comparable results were obtained for all SCS-SA soil groups. In the Mpumalanga simulations, highly comparable results are obtained for SCS-SA soil groups A/B and D only. The results for the remainder of the SCS-SA soil groups are still nonetheless comparable, with the exception of SCS-SA soil group C/D. The poorest simulation comparison was obtained for SCS-SA soil group C/D, with the results being just outside of the comparable range and slightly into the poorly comparable range. As stated in the previous chapter, this trend is to be expected since each simulation comparison for Quinary 4854 in KZN was optimised individually through calibration and consequently the comparisons are expected to be more similar. The simulation results depicted in Figure 7.16 are nonetheless once again comparable, whilst importantly still maintaining the desired trend of increasing runoff from an "*ACRU* A soil group" (Poor_*QFRESP* = 0.70) to an "*ACRU* D soil group" (Poor_*QFRESP* = 1; *SMDDEP* = 0.12).

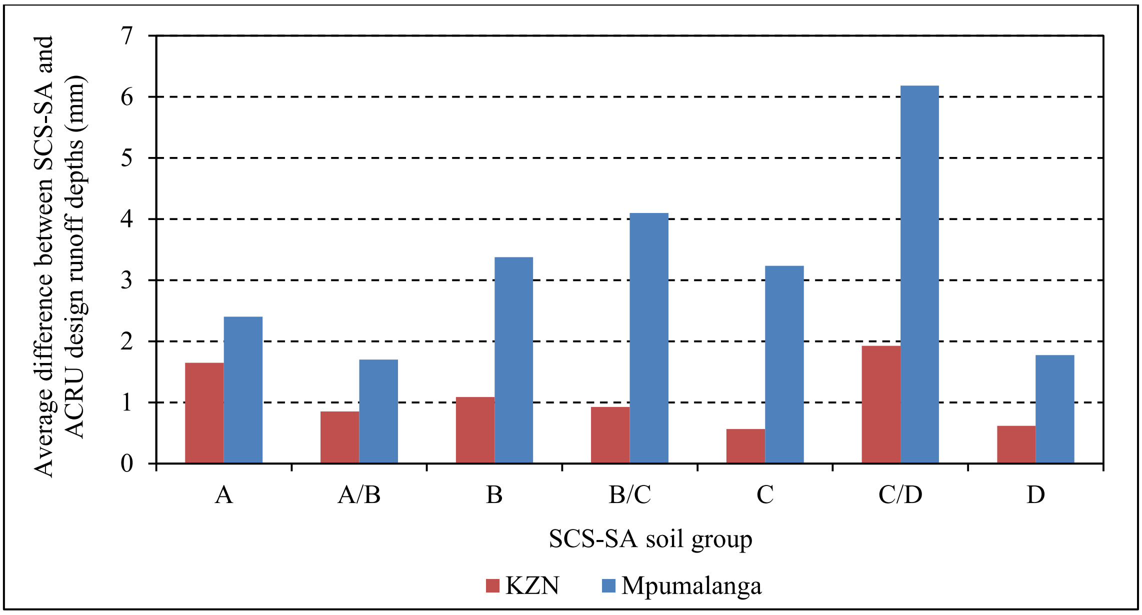


Figure 7.17 Average absolute difference between SCS-SA and *ACRU* design runoff simulations (averaged for the 2 – 100 year return periods) for a veld land cover in poor condition in the KZN and Mpumalanga provinces for SCS-SA soil groups A to D

The results for a veld land cover in poor hydrological condition further validate the application of the rules developed so far to represent SCS-SA soil groups in *ACRU* at different geographical locations. The validation procedure, however, needs to be extended to a more drastic change in location such as a winter rainfall region in the Western Cape. Subsequently, the following chapter aims to further validate the previously implemented procedure in the Western Cape for a veld/grassland land cover and develop a new set of rules for a common commercial crop cultivated in the Western Cape, namely wheat, *i.e.* an equivalent to maize in the eastern summer rainfall regions of the country.

7.3 Consistency Testing: Western Cape

Figure 7.18 depicts the location of a randomly selected Quinary, G22F3 (Quinary number – 2697 in the QCD) situated within the Western Cape. The default climate information and other physical attributes of Quinary 2697, available from the QCD, were used in the *ACRU* simulations. The daily rainfall file assigned to Quinary 2697, used as the input into the *ACRU* model, was used to calculate the design rainfall input values for the SCS-SA model.

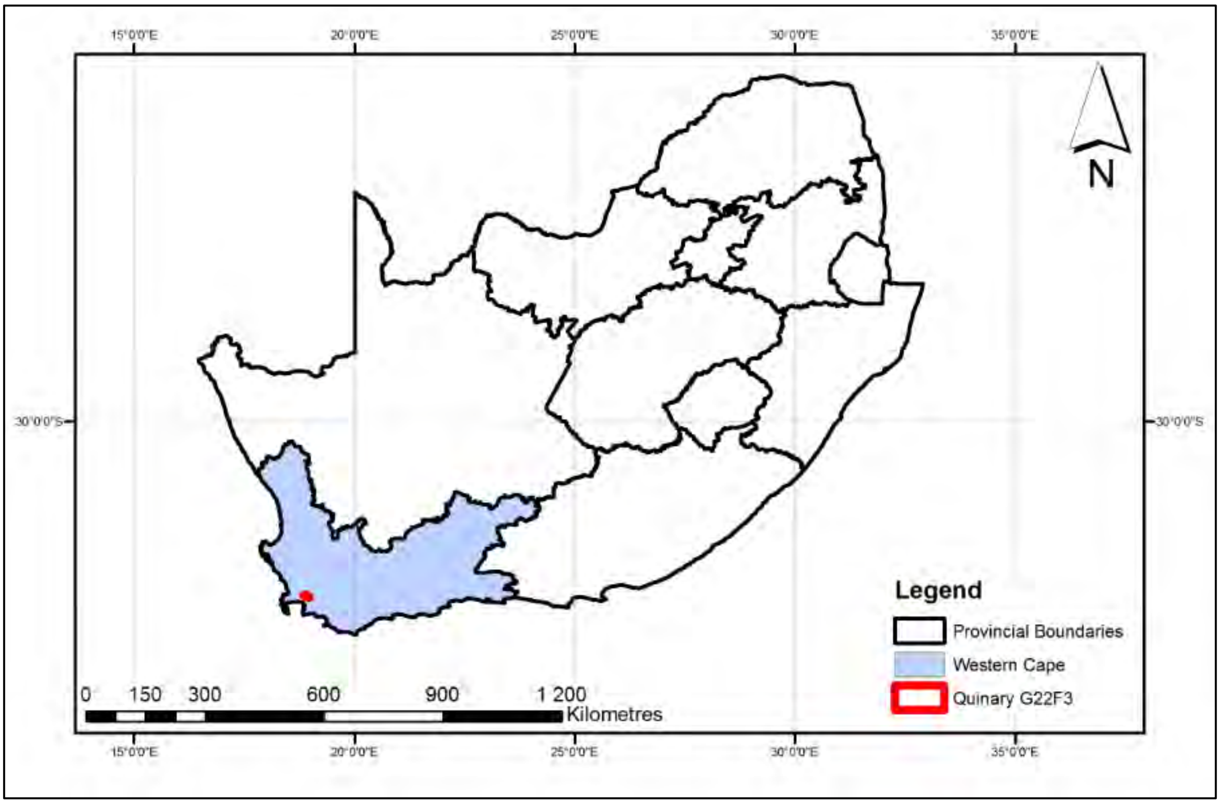


Figure 7.18 Location map of Quinary G22F3 (MAP – 973mm) in the Western Cape, South Africa

The objective of this investigation is to once again determine if the *QFRESP* and *SMDDEP* values found to represent SCS-SA soil groups for a veld land cover in KZN, and validated to adequately represent SCS-SA soil groups for a veld land cover in Mpumalanga, may be directly transferred and used under the contrasting climatic conditions found within the Western Cape. A veld/grassland land cover in fair hydrological condition was once again investigated.

7.3.1 Veld/Grassland land cover in fair condition

Figure 7.19 illustrates the design runoff trends calculated by the SCS-SA model for a Veld land cover, in fair hydrological condition, for SCS-SA soil groups A to D at specific return periods, along with the input design rainfall estimated for Quinary 2697, Western Cape.

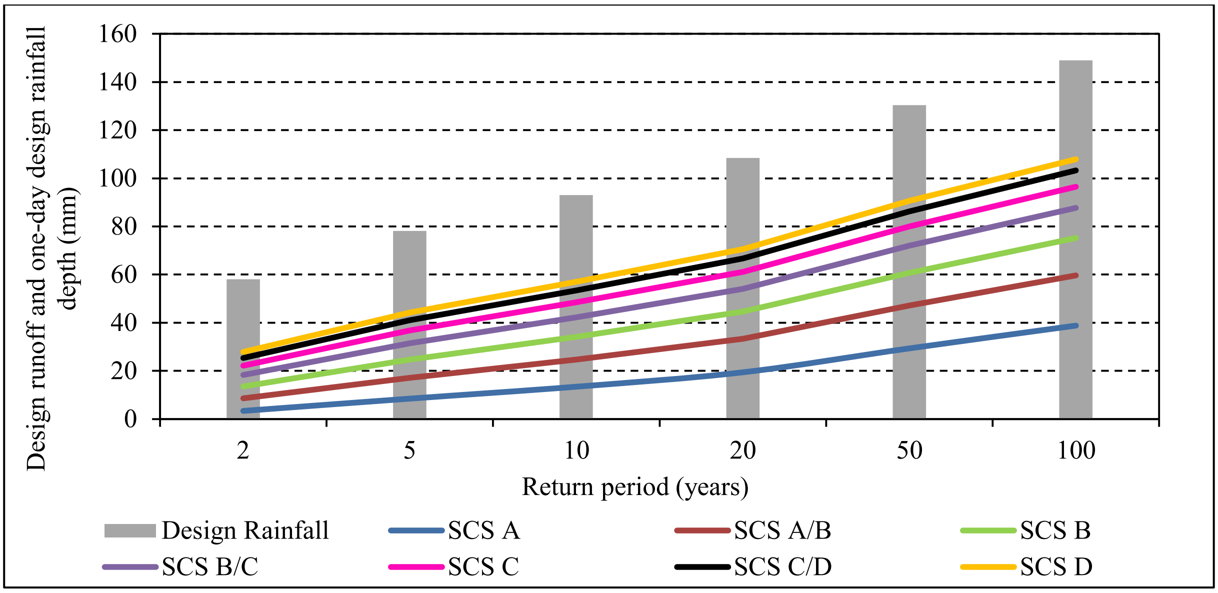


Figure 7.19 SCS-SA hydrological responses computed for a veld land cover, in fair hydrological condition, for soil groups A – D at specific return periods and the causative design rainfall, Quinary 2697, Western Cape

The *QFRESP* and *SMDDEP* values "calibrated" to represent SCS-SA soil groups A to D best for a veld land cover in fair condition from the KZN simulations, as summarised in Table 7.1, were once again used to simulate design runoff volumes in the *ACRU* model. Figure 7.20 compares the *ACRU* simulation results for the assigned *QFRESP* and *SMDDEP* values from Table 7.1 with the corresponding SCS-SA simulation results as depicted in Figure 7.19. The results presented in Figure 7.20 show that there is high correlation between the SCS-SA and *ACRU* model results, when applying the calibrated *QFRESP* and *SMDDEP* values from Quinary 4854, KZN (Table 7.1). Figure 7.21 compares the average absolute differences between SCS-SA and *ACRU* design runoff volumes for each SCS-SA soil group for all three provinces investigated thus far. The results, as expected, show that the average absolute differences in runoff responses between the *ACRU* and SCS-SA models for the Western Cape are consistently higher than those calculated for KZN, again attributed to the fact that the KZN simulations were individually calibrated until optimal simulation comparisons were achieved. The Western Cape and Mpumalanga average differences are generally fairly similar especially for SCS-SA soil groups B/C to D (Figure 7.21); while for SCS-SA soil groups A to B, the Mpumalanga average differences are lower than those calculated for the Western Cape. Despite there being clear differences between the results for the three provinces the differences all fall within the comparable range, with the desired trends being maintained, *i.e.* increasing design runoff volumes going from SCS-SA soil group A to SCS-SA soil group D.

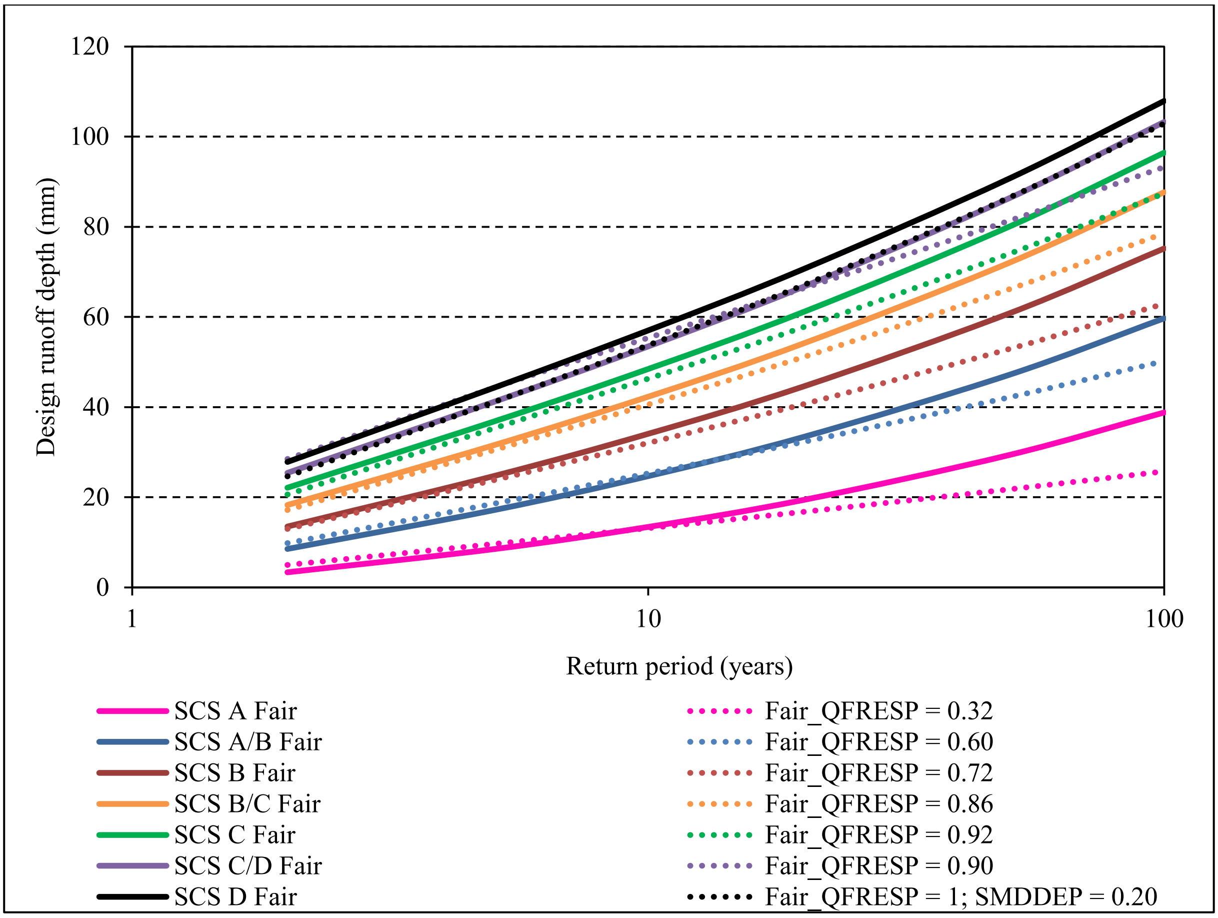


Figure 7.20 SCS-SA and *ACRU* design runoff comparisons for a veld in fair condition and SCS-SA soil groups A to D for Quinary 2697, Western Cape

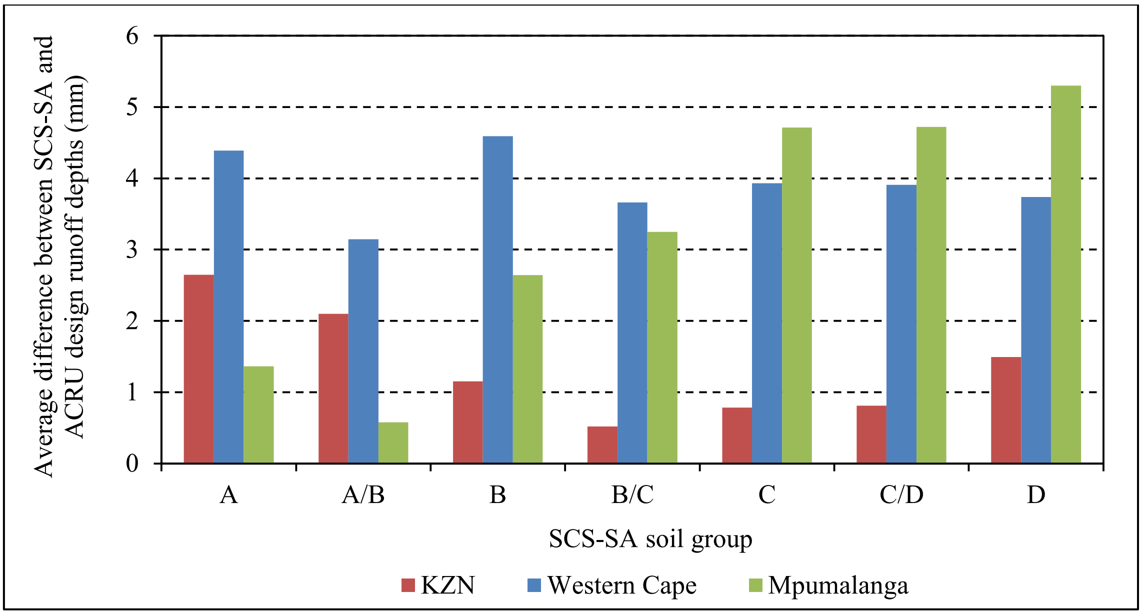


Figure 7.21 Average absolute difference between SCS-SA and *ACRU* design runoff simulations (averaged for the 2 – 100 year return periods) for a veld in good condition in the KZN, Mpumalanga and Western Cape provinces for SCS-SA soil groups A to D

Ultimately the validation results presented in the preceding sections support the rules developed to represent SCS-SA soil groups for a veld/grassland land cover. Having expended considerable efforts towards the analysis of a veld/grassland land cover, an extremely important and widely distributed land cover within South Africa, the need to investigate an alternative land cover of particular importance to the Western Cape was identified. As stated in the previous chapters, an important agricultural crop cultivated in the Western Cape is wheat, which is often considered as an equivalent to maize in the eastern parts of South Africa. Subsequently the following section compares the SCS-SA and *ACRU* simulation results for a wheat crop.

7.3.2 Small Grain/Wheat land cover

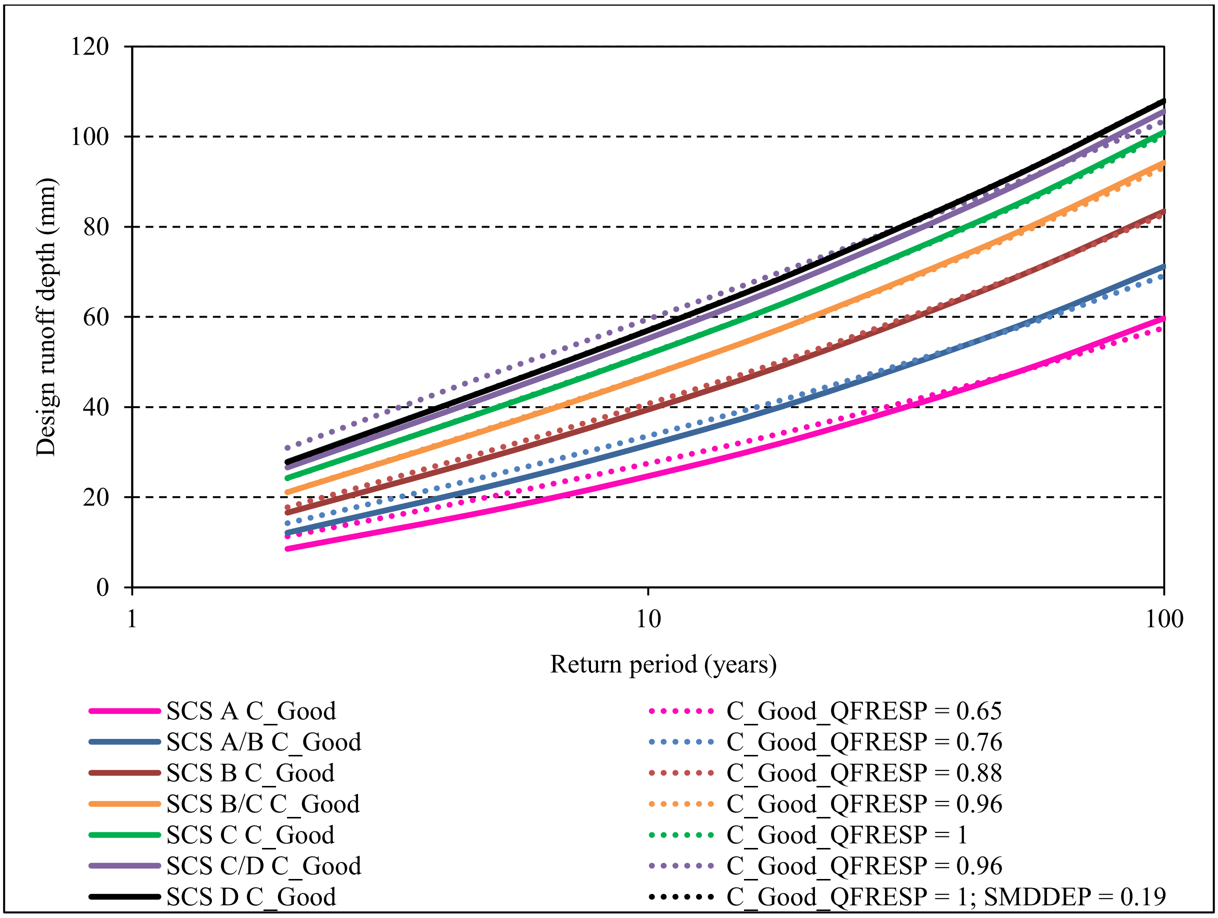
In the SCS-SA land cover classification, there are several different classes within the general wheat/small grain land cover class, for different land management practices and stormflow potentials/hydrological conditions (Schulze *et al.*, 2004), identical to the classes for a row crop (Table 3.1). The same approach applied in the previous chapter for a veld/grassland land cover was used in this analysis for a wheat crop land cover, however in this case again calibrating the *QFRESP* and *SMDDEP* values in the *ACRU* model to represent each SCS-SA soil group for a wheat crop, planted on the contour in good hydrological condition. This land cover class was selected based on the assumption that this land cover class is commonly encountered within wheat cultivated lands in the Western Cape, particularly within the commercial wheat production sector. The default *ACRU* model input values for a general wheat crop planted in June, COMPOVEG crop number 3020204, were used to represent a wheat/small grain land cover in good hydrological condition, *i.e.* a low stormflow potential.

To represent a wheat/small grain crop in poor hydrological condition it is suggested that the *CAY* and *VEGINT* variables be adjusted from the defaults applying the same rules used to represent a maize/row crop in poor condition, as summarised below:

(i) *CAY* to be reduced by 10%, but with the provision that *CAY* values are not allowed to drop below 0.2 in any month; and
(ii) *VEGINT* to be reduced by 20% in all months.

Once again, these adjustments alone result in negligible differences in design runoff responses, however, it is considered that conceptually these variables would be influenced by hydrological condition. In this section, comparison of the SCS-SA and *ACRU* results were investigated for a wheat/small grain crop planted on the contour in good hydrological condition. Further investigation with other classes is believed to be unnecessary and redundant since previous analyses have proven that if the calibration procedure works for one class of a specific land cover, it will be applicable for the other classes. Furthermore sufficient information has been obtained to identify trends and to perform statistical analyses on the results to determine if there is a relationship between the calibrated *QFRESP* and *SMDDEP* values and corresponding CNs, which will be investigated in the following section.

Figure 7.22 compares the simulation results from the SCS-SA model for a wheat/small grain crop in good condition, planted on the contour and SCS-SA soil groups A to D with the calibrated simulation results from the *ACRU* model. The results (Figure 7.22) once again show that similar simulation results are obtained when calibrating *QFRESP* and *SMDDEP* variables to represent SCS-SA soil groups for a wheat/small grain crop in good hydrological condition, planted on the contour. The significance of the similarity between the SCS-SA and *ACRU* design runoff volumes from Figure 7.22 is captured in Figure 7.23, where the average absolute differences between SCS-SA and *ACRU* design runoff volumes are depicted. As seen in Figure 7.23 the SCS-SA and *ACRU* simulation results are comparable for SCS-SA soil groups A and C/D and highly comparable for the remaining SCS-SA soil groups.



*C_Good: Planted on the contour, in good condition

Figure 7.22 SCS-SA and *ACRU* design runoff comparisons for a wheat land cover, planted on the contour, in good condition and SCS-SA soil groups A to D for Quinary 2697, Western Cape

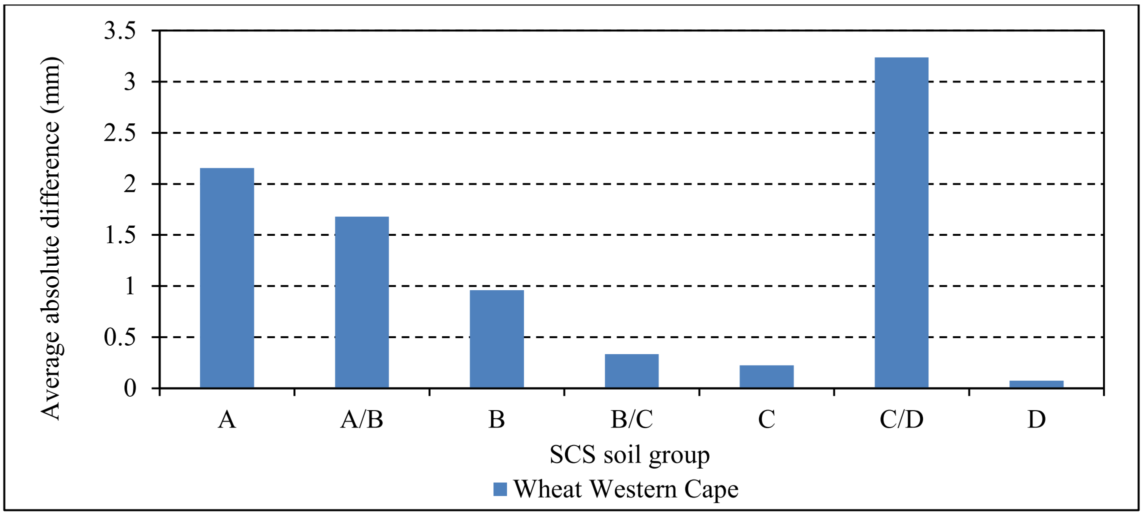


Figure 7.23 Average absolute difference between SCS-SA and *ACRU* design runoff simulations (averaged for the 2 – 100 year return periods) for a wheat land cover, planted on the contour, in good condition, Quinary 2697, Western Cape

The results for a wheat/small grain land cover continue to support the hypothesis that the *ACRU QFRESP* and *SMDDEP* variables may be used to represent SCS-SA soil groups and the associated CNs for different land cover classes, hydrological conditions and management practices. As alluded to above, however, there is a need to compile the results obtained thus far and investigate if there is a relationship between SCS-SA CNs and the calibrated *QFRESP* and *SMDDEP* values found to represent these CNs. Subsequently the following section focuses on the identification of trends and statistical analysis of the results presented thus far.

7.4 Statistics and Trend Analysis

Table 7.3 summarises the results for several of the land cover classes investigated thus far. Included in the table are the original CNs for each SCS-SA land cover class and the corresponding *QFRESP* and *SMDDEP* values calibrated to represent each SCS-SA soil group for that land cover class. An additional column with a predicted CN is also included. The values in this column were obtained from a multiple linear regression analysis performed on the original CNs (the dependent variable) and corresponding *QFRESP* and *SMDDEP* values (the independent variables) summarised in Table 7.3. The statistics and output from the multiple linear regression analysis are presented in Table 7.4 and are discussed below.

Table 7.3 SCS-SA and *ACRU* input value summary results

SCS-SA Land Cover Class	Stormflow Potential	SCS-SA Soil Group	SCS-SA CN	*ACRU* *QFRESP*	*ACRU* *SMDDEP*	Predicted CN
Veld/pasture in fair condition	Moderate	A	49	0.32	0.25	48
Veld/pasture in poor condition	High	A	68	0.70	0.25	66
Maize Planted on contour	Low	A	65	0.72	0.25	67
Maize Planted on contour	High	A	70	0.87	0.25	74
Maize Straight row	Low	A	67	0.78	0.25	70
Veld/pasture in good condition	Low	A	39	0.30	0.35	41
Wheat Planted on contour	Low	A	61	0.65	0.25	64
Maize Straight row	High	A	72	0.92	0.25	76
Veld/pasture in fair condition	Moderate	A/B	61	0.60	0.25	62
Veld/pasture in poor condition	High	A/B	74	0.88	0.25	75
Maize Planted on contour	Low	A/B	69	0.80	0.25	71
Maize Planted on contour	High	A/B	75	0.96	0.25	78
Maize Straight row	Low	A/B	73	0.91	0.25	76
Veld/pasture in good condition	Low	A/B	51	0.35	0.25	50
Wheat Planted on contour	Low	A/B	67	0.76	0.25	69
Maize Straight row	High	A/B	77	1.00	0.23	82
Veld/pasture in fair condition	Moderate	B	69	0.72	0.25	67
Veld/pasture in poor condition	High	B	79	1.00	0.25	80
Maize Planted on contour	Low	B	75	0.92	0.25	76
Maize Planted on contour	High	B	79	1.00	0.22	82
Maize Straight row	Low	B	78	1.00	0.24	81
Veld/pasture in good condition	Low	B	61	0.58	0.25	61
Wheat Planted on contour	Low	B	73	0.88	0.25	75
Maize Straight row	High	B	81	1.00	0.19	84
Veld/pasture in fair condition	Moderate	B/C	75	0.86	0.25	74
Veld/pasture in poor condition	High	B/C	83	1.00	0.22	82
Maize Planted on contour	Low	B/C	79	1.00	0.25	80
Maize Planted on contour	High	B/C	82	1.00	0.21	83
Veld/pasture in good condition	Low	B/C	68	0.70	0.25	66
Wheat Planted on contour	Low	B/C	78	0.96	0.25	78
Maize Straight row	Low	B/C	82	1.00	0.21	83
Maize Straight row	High	B/C	85	1.00	0.16	86
Veld/pasture in fair condition	Moderate	C	79	0.92	0.25	76
Veld/pasture in poor condition	High	C	86	1.00	0.18	85
Maize Planted on contour	Low	C	82	1.00	0.23	82
Maize Planted on contour	High	C	84	1.00	0.19	84
Veld/pasture in good condition	Low	C	74	0.80	0.25	71
Wheat Planted on contour	Low	C	81	1.00	0.25	80
Maize Straight row	Low	C	85	1.00	0.17	86
Maize Straight row	High	C	88	1.00	0.13	88

Table 7.3 Continued

SCS-SA Land Cover Class	Stormflow Potential	SCS-SA Soil Group	SCS-SA CN	*ACRU QFRESP*	*ACRU SMDDEP*	Predicted CN
Veld/pasture in fair condition	Moderate	C/D	82	0.90	0.25	75
Veld/pasture in poor condition	High		88	1.00	0.22	82
Maize Planted on contour	Low		84	1.00	0.25	80
Veld/pasture in good condition	Low		78	0.80	0.25	71
Wheat Planted on contour	Low		83	0.96	0.25	78
Maize Planted on contour	High		86	1.00	0.22	82
Maize Straight row	Low		87	1.00	0.19	84
Maize Straight row	High		90	1.00	0.14	88
Veld/pasture in fair condition	Moderate	D	84	1.00	0.20	84
Veld/pasture in poor condition	High		89	1.00	0.12	89
Maize Planted on contour	Low		86	1.00	0.15	87
Veld/pasture in good condition	Low		80	1.00	0.25	80
Wheat Planted on contour	Low		84	1.00	0.19	84
Maize Planted on contour	High		88	1.00	0.12	89
Maize Straight row	Low		89	1.00	0.11	90
Maize Straight row	High		91	1.00	0.08	92

Table 7.4 Multiple linear regression statistics and derived coefficients

Regression Statistics	
Multiple R	0.97
R^2	0.94
Standard Error	2.66
Observations	56.00
Coefficients	
Intercept	50.37
X Variable 1(*QFRESP*)	46.60
X Variable 2(*SMDDEP*)	-67.26

The results from the multiple linear regression analysis (Table 7.4), performed in Microsoft Excel, show that a strong linear relationship was found between SCS-SA CNs and the *QFRESP* and *SMDDEP* values calibrated to represent SCS-SA soil groups best. This is identified by the high coefficient of determination (R^2 = 0.94) as well as the relatively small standard error (2.66).

Using the coefficients optimised and output by the linear regression analysis (Table 7.4), the following linear equation was developed to estimate "predicted" CN values for given *QFRESP* and *SMDDEP* combinations:

$$CN = 46.60(QFRESP) - 67.26(SMDDEP) + 50.37 \qquad (7.1)$$

Equation 7.1 was used to calculate the predicted CN values listed in Table 7.3 using the corresponding *QFRESP* and *SMDDEP* values from Table 7.3. The actual CN values and predicted CN values (Table 7.3) were plotted against one another and the results are depicted in Figure 7.24. Figure 7.24 depicts the statistics from Table 7.4 graphically and reinforces the point that there is a strong linear relationship between the actual CN values and derived *QFRESP* and *SMDDEP* variables, *i.e.* used to calculate the predicted CN values.

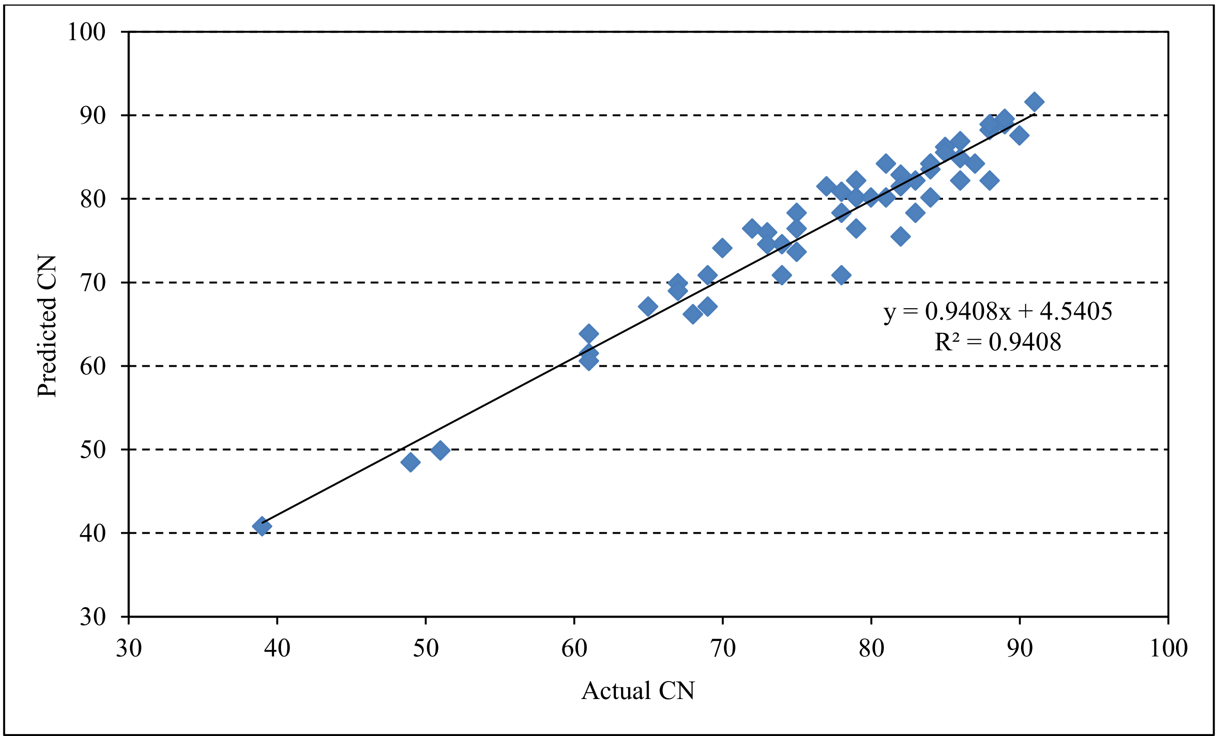


Figure 7.24 Predicted CN values versus SCS-SA CN values

A t-Test statistical analysis was performed on the actual and predicted CN values from Table 7.3 to statistically determine if there is a significant difference between the two data sets. The results from the t-Test are presented in Table 7.5.

Table 7.5 t-Test statistical output

t-Test: Paired Two Sample for Means		
	Variable 1 (Actual CN)	*Variable 2 (Predicted CN)*
Mean	76.66	76.66
Variance	115.46	108.63
Observations	56.00	56.00
Pearson Correlation	0.97	
Hypothesized Mean Difference	0.00	
df	55.00	
t Stat	-4.21E-14	
P(T<=t) two-tail	1.00	
t Critical two-tail	2.00	

From Table 7.5, it can be seen that the Mean of Variable 1, the Actual CN dataset (76.66), is identical to that of Variable 2, the Predicted CN dataset (76.66). The Variance of the Actual CN dataset is slightly larger (115.46) than that of the Predicted CN dataset (108.63). There are 55 degrees of freedom (df). The t Stat value is -4.21E-14, which is significantly smaller than the t Critical two-tail value of 2.00 and the P(T<=t) two-tail value is 1.00, which is larger than the alpha value (0.05). Therefore, we can confirm at the 95% confidence interval that there is no significant difference between the two datasets.

The statistical analyses have shown that there is a strong relationship between SCS-SA CNs and *ACRU QFRESP* and *SMDDEP* variables. In Chapter 7.1.4, it was stated that difficulty comparing the design runoff responses from the *ACRU* and SCS-SA models for a sugarcane land cover was encountered and required input from statistical analysis of the results obtained from successful calibrations. Subsequently, having performed the statistical analyses and developing a relationship between CN values and *QFRESP* and *SMDDEP* values (Equation 7.1) the sugarcane analyses will now be presented in the following chapter.

7.5 Sugarcane Land Cover KwaZulu-Natal

As stated in the previous chapter, initial difficulty was encountered when comparing the SCS-SA and *ACRU* simulation results for a sugarcane land cover. The main reason for this being that the runoff generated from sugarcane in the SCS-SA model is characteristically very low, represented by low CN values, especially when there is high cover and conservation structures have been used (Table 7.6).

Table 7.6 Initial CNs for the SCS-SA sugarcane land cover classes (after Schulze *et al.*, 2004)

Land Cover Class	**Land Treatment/Practice/Description**	**Stormflow Potential**	**Hydrological Soil Group**						
			A	**A/B**	**B**	**B/C**	**C**	**C/D**	**D**
Sugarcane	1 = Straight row: trash burnt	-	43	55	65	72	77	80	82
	2 = Straight row: trash mulch	-	45	56	66	72	77	80	83
	3 = Straight row: limited cover	-	67	73	78	82	85	87	89
	4 = Straight row: partial cover	-	49	60	69	73	79	82	84
	5 = Straight row: complete cover	-	39	50	61	68	74	78	80
	6 = Conservation structures: limited cover	-	65	70	75	79	82	84	86
	7 = Conservation structures: partial cover	-	25	46	59	67	75	80	83
	8 = Conservation structures: complete cover	-	6	14	35	59	70	75	79

When using the SCS-SA model to estimate design runoff volumes, however, using a CN value lower than 50 is not recommended (Schmidt and Schulze, 1987a) in order to be conservative in terms of the runoff estimates. Nonetheless an attempt was made to represent the lowest possible CN value in the *ACRU* model. Therefore as a starting point, sugarcane land cover class seven (Conservation structures: partial cover) was selected for analysis, since for a SCS-SA A soil the CN value (25) is well below 50 and then rises accordingly for SCS-SA soil groups A/B to D. To represent a sugarcane land cover in the SCS-SA model, the same model set-up as used for a veld/grassland land cover in KZN was used, however, changing the CN values to those of a sugarcane land cover. Similarly, to represent a sugarcane land cover in the *ACRU* model, the same model set-up and climate file as used in the *ACRU* simulations for a veld/grassland land cover in KZN were used, however, the vegetation properties were changed to those of an inland sugarcane crop, COMPOVEG crop number 5200704. The vegetation and *SMDDEP* properties for this land cover class as described by Schulze (2013) from verification studies by Schmidt *et al.* (1998) are summarised in Table 7.7.

Table 7.7 Values assigned to *ACRU* variables for sugarcane crop number 5200704 (after Schulze, 2013)

***ACRU* Variable**	**KZN Inland**
CAY	0.83
VEGINT	1.70
ROOTA	0.75
COIAM	0.35
PCSUCO	90.00
SMDDEP	0.35

As seen in Table 7.7, Schulze (2013) recommends using a *COIAM* of 0.35 in all months and a *SMDDEP* value of 0.35 assuming: (i) all variables as intra-seasonally averaged values; (ii) the sugarcane is burnt at harvest and with a mix of 50% conservation tillage and 50% minimum tillage; and (iii) contour banks are assumed since sugarcane is frequently grown on sloping terrain. When using these *COIAM* and *SMDDEP* values, however, to simulate design runoff volumes in the *ACRU* model, the model "crashes", *i.e.* fails to output results. This occurs due to the following reasons. For the smaller design rainfall events no, or very low, runoff volumes are generated. Consequently when attempting to determine the LP-III extreme value distribution from the AMS, there are zero or near zero values within the AMS. Since a log transformation of the AMS is required to fit an LP-III distribution to the data, the model crashes and outputs a value of 1 as an error message, since taking the log of a zero value is not possible. Furthermore, very low or near zero values strongly skew the data, which results in a distribution that fits the AMS poorly. Attempts were made to manually remove these zero, or near zero, values and subsequently manually fit the LP-III distribution. The results, however, were not encouraging, *i.e.* similar design runoff responses between the *ACRU* and SCS-SA models could not be obtained. It also became evident that inaccurate and inconsistent LP-III distributions were being estimated by removing certain values from the AMS.

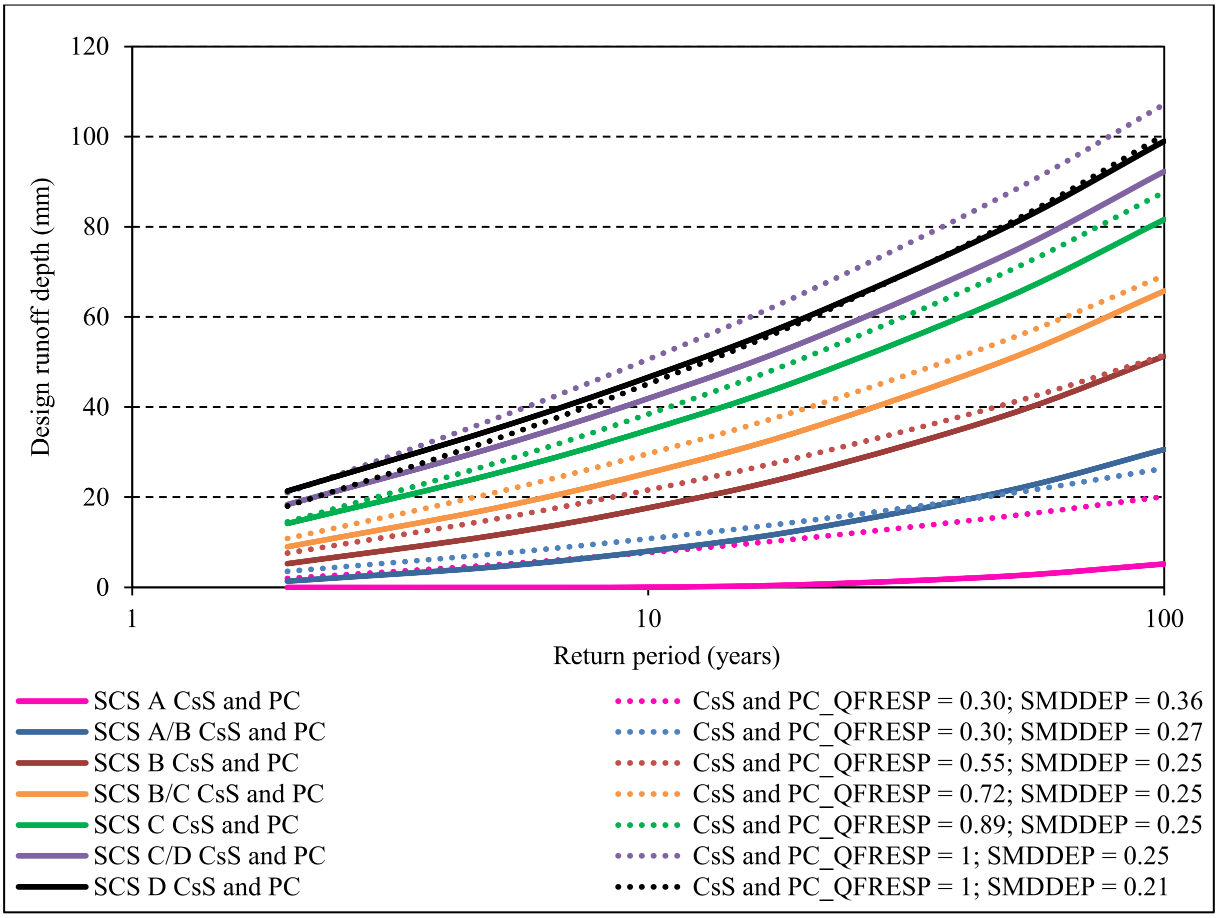
Further investigation identified that simultaneously increasing both the *COIAM* and *SMDDEP* to 0.35 should be avoided in this investigation due to the following reason; increasing *SMDDEP* or the *COIAM* individually results in increased infiltration and reduced runoff, however, this impact is magnified significantly when both these variables are increased simultaneously. A decision was therefore made to adjust the *COIAM* to values similar to those implemented for a maize crop in the KZN simulations and determine if the linear relationship (Equation 7.1) identified in Chapter 7.4 may be used to estimate *QFRESP* and *SMDDEP* values to represent the CNs for the selected sugarcane land cover class. In order to do this, however, some rules needed to be developed since there are three variables in Equation 7.1 and consequently to estimate any given variable, the values of the other two variables must be known. Using the results and trends from Chapter 7.4, and particularly Table 7.3, the following rules were derived and are summarised in Table 7.8.

Table 7.8 Rules developed to determine *QFRESP* and *SMDDEP* values for selected CNs

Rules	**CN 40 - 48**	**CN 48 - 80**	**CN > 80**
	***QFRESP* = 0.3**	***SMDDEP* = 0.25**	***QFRESP* = 1**
Input CN	46	80	82
Rearrange Equation 7.1 to solve for *SMDDEP or QFRESP*	*SMDDEP*	*QFRESP*	*SMDDEP*
Calculated value	0.27	1.00	0.22

From Table 7.8, it is evident that rules were developed for different CN ranges. The first range of CN values being those ranging from 40 – 48. It is recommended that CN values lower than 40 should not be simulated due to erroneous results being obtained below this value. For this range of CN values, the rules state that a fixed *QFRESP* value of 0.3 must be used and Equation 7.1 must be rearranged in order to solve for *SMDDEP*. An example is shown in Table 7.8 where an estimated *SMDDEP* value of 0.27 is calculated for an input CN value of 46, after rearranging Equation 7.1 to solve for *SMDDEP*. For CNs ranging from 48 – 80, the rules state that *SMDDEP* must remain fixed at a value of 0.25 and Equation 7.1 must be rearranged in order to solve for *QFRESP*. An example is shown for a CN value of 80, where the *QFRESP* value is calculated to be 1.00. For CN values greater than 80, the rules state that *QFRESP* must remain fixed at 1.00 and Equation 7.1 must be rearranged in order to once again solve for *SMDDEP*.

Figure 7.25 compares the SCS-SA and *ACRU* design runoff volumes for a sugarcane land cover with Conservation Structures and Partial Cover, applying the rules summarised in Table 7.8 and changing the *COIAM* values for a sugarcane land cover (crop number 5200704) in the *ACRU* simulations to those used for a maize crop in KZN.



*CsS and PC: Conservation Structures and Partial Cover

Figure 7.25 SCS-SA and *ACRU* design runoff comparisons for a sugarcane land cover, with Conservation Structures and Partial Cover for SCS-SA soil groups A to D, Quinary 4854, KZN

SCS-SA soil group A for a sugarcane land cover with Conservation Structures and Partial Cover has a CN value of 25 (Table 7.6), the rules described in Table 7.8, however, recommend that CN values lower than 40 should not be used. Subsequently, a CN value of 40 was used with the rules described in Table 7.8 to represent a SCS-SA A soil group. For this reason, the SCS-SA and *ACRU* simulation results for a SCS-SA A soil group are poorly comparable (Figure 7.26). This is, however, considered to be acceptable realising that erroneous results would be obtained in attempting to represent CNs lower than 40. Furthermore, it is considered preferable to be conservative in terms of the design flood estimates. SCS-SA soil groups A/B to D, however, were found to produce comparable results when applying the rules described in Table 7.8, with the exception of SCS-SA soil group C/D (Figure 7.26). For SCS-SA soil group C/D, the *ACRU* simulation results are noticeably higher than the SCS-SA simulation results. The average absolute differences calculated for the calibrated *ACRU* and SCS-SA results for a veld/grassland land cover in fair condition in KZN have been included in Figure 7.26 for comparison with the sugarcane results.

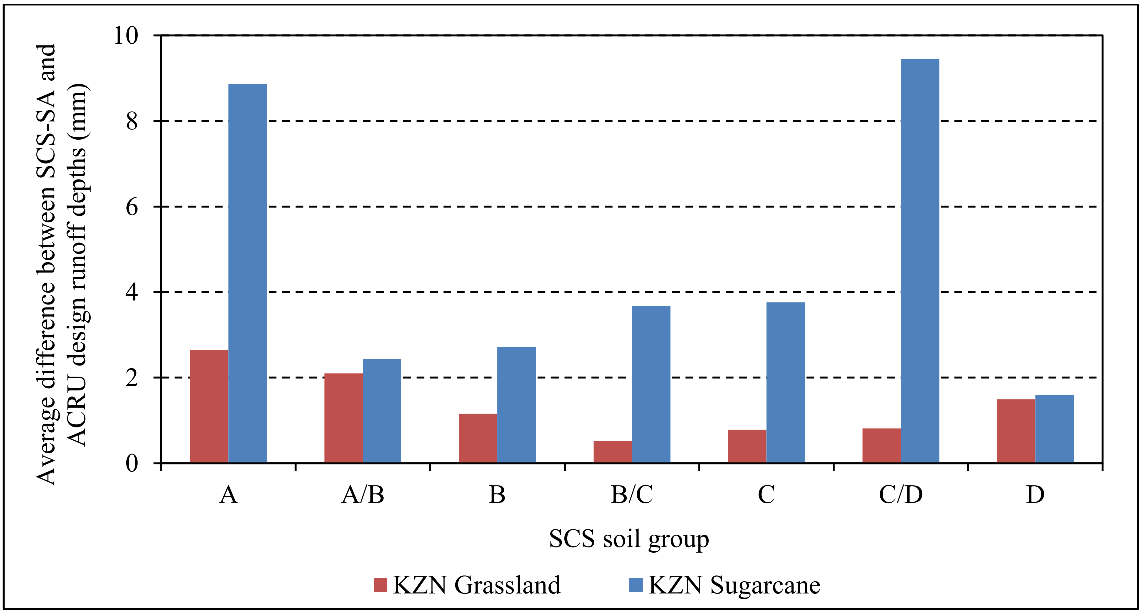


Figure 7.26 Average absolute difference between SCS-SA and *ACRU* design runoff simulations (averaged for the 2 – 100 year return periods) for a veld in good condition and a sugarcane land cover with Conservation Structures and Partial Cover in KZN for SCS-SA soil groups A to D

In addition to the poor comparison between the SCS-SA and *ACRU* results for SCS-SA soil group C/D, the *ACRU* simulation results for SCS-SA soil group C/D are larger than the simulation results for SCS-SA soil group D (Figure 7.25). This is conceptually incorrect since it diverges from the general trend of increasing runoff from SCS-SA soil groups A to D. This may once again be attributed to the inconsistencies related to the SCS-SA C/D soil group in terms of textural properties, *i.e.* as detailed in Chapter 5.2 and Chapter 7.1.1 the textural properties assigned to SCS-SA soil group C/D, through the Binomial approach, are considerably different and inconsistent to the general trends. Consequently, these inconsistencies continue to re-emerge in further analyses, such as in this case. An important observation, however, was made with regards to the statistical analyses presented in Chapter 7.4. Closer analysis of the comparison between actual and predicted CNs (Figure 7.24) revealed that although there was high correlation between the predicted and actual CNs for all SCS-SA soil groups, a few points deviated from the general trend slightly more than the other points. After further investigation, it was discovered that these points belonged to the SCS-SA

C/D soil group. It therefore became evident that the SCS-SA C/D soil group follows a slightly different trend to the other SCS-SA soil groups due to the anomalous textural properties of the SCS-SA C/D soils, as previously described. In this analysis, however, the anomaly has been accounted for and factored-in through the calibration procedure. Since the SCS-SA C/D soils are a special case, a decision was made to separate the SCS-SA C/D soils from the other soil groups. A multiple linear regression analysis was therefore once again performed on the results listed in Table 7.3, however, in this case omitting the results for SCS-SA soil group C/D. The results (Table 7.9) show that the relationship is even stronger when omitting the results for SCS-SA soil group C/D. This is identified by the higher coefficient of determination (R^2 = 0.97) depicted in Table 7.9 compared to the coefficient of determination (R^2 = 0.94) from Table 7.4, as well as the smaller standard error 1.88 (Table 7.9) compared to 2.66 (Table 7.4).

Table 7.9 Multiple linear regression statistics and derived coefficients after omitting SCS-SA C/D soil results

Regression Statistics	
Multiple R	0.99
R^2	0.97
Standard Error	1.80
Observations	48.00
Coefficients	
Intercept	53.78
X Variable 1(*QFRESP*)	43.91
X Variable 2(*SMDDEP*)	-75.52

Using the coefficients optimised and output by the revised linear regression analysis (Table 7.9) a new linear equation was developed to estimate "predicted" CN values for given *QFRESP* and *SMDDEP* combinations for all SCS-SA soil groups, excluding SCS-SA soil group C/D:

$$CN = 43.91(QFRESP) - 75.52(SMDDEP) + 53.78 \qquad (7.2)$$

In addition to deriving a new equation, a new set of rules were required to accompany Equation 7.2. The following revised rules were determined for all SCS-SA soil groups, excluding SCS-SA soil group C/D (Table 7.10).

Table 7.10 Revised rules developed to determine *QFRESP* and *SMDDEP* values for CNs corresponding to all SCS-SA soil groups, excluding SCS-SA soil group C/D

Rules	**CN 40 - 48**	**CN 48 - 79**	**CN > 79**
	***QFRESP* = 0.3**	***SMDDEP* = 0.25**	***QFRESP* = 1**
Input CN	46	79	79
Rearrange Equation 7.2 to solve for *SMDDEP or QFRESP*	*SMDDEP*	*QFRESP*	*SMDDEP*
Calculated value	0.28	1.00	0.25

The rules summarised in Table 7.10 are very similar to those derived in Table 7.8, however, the CN ranges are slightly different, *e.g.* CN 48 – 79 instead of CN 48 – 80 and CN > 79 instead of CN > 80, and the prediction equation is different.

Having revised the rules for all SCS-SA soil groups excluding SCS-SA soil group C/D, the next step was to develop rules for this soil group. Using the results from Table 7.3 for SCS-SA soil group C/D only, an additional multiple linear regression analysis was performed with the results summarised in Table 7.11. Once again a strong linear relationship was found between SCS-SA CNs and the *QFRESP* and *SMDDEP* values calibrated to represent SCS-SA soil group C/D best. This is identified by the high coefficient of determination (R^2 = 0.95) as well as the small standard error (0.98).

Table 7.11 Multiple linear regression statistics and derived coefficients for SCS-SA soil group C/D

Regression Statistics	
Multiple R	0.98
R^2	0.95
Standard Error	0.98
Observations	8.00
Coefficients	
Intercept	63.91
X Variable 1(*QFRESP*)	32.92
X Variable 2(*SMDDEP*)	-48.28

Using the coefficients optimised and output by the linear regression analysis (Table 7.11), the following linear equation was developed to estimate "predicted" CN values for given *QFRESP* and *SMDDEP* combinations for SCS-SA soil group C/D:

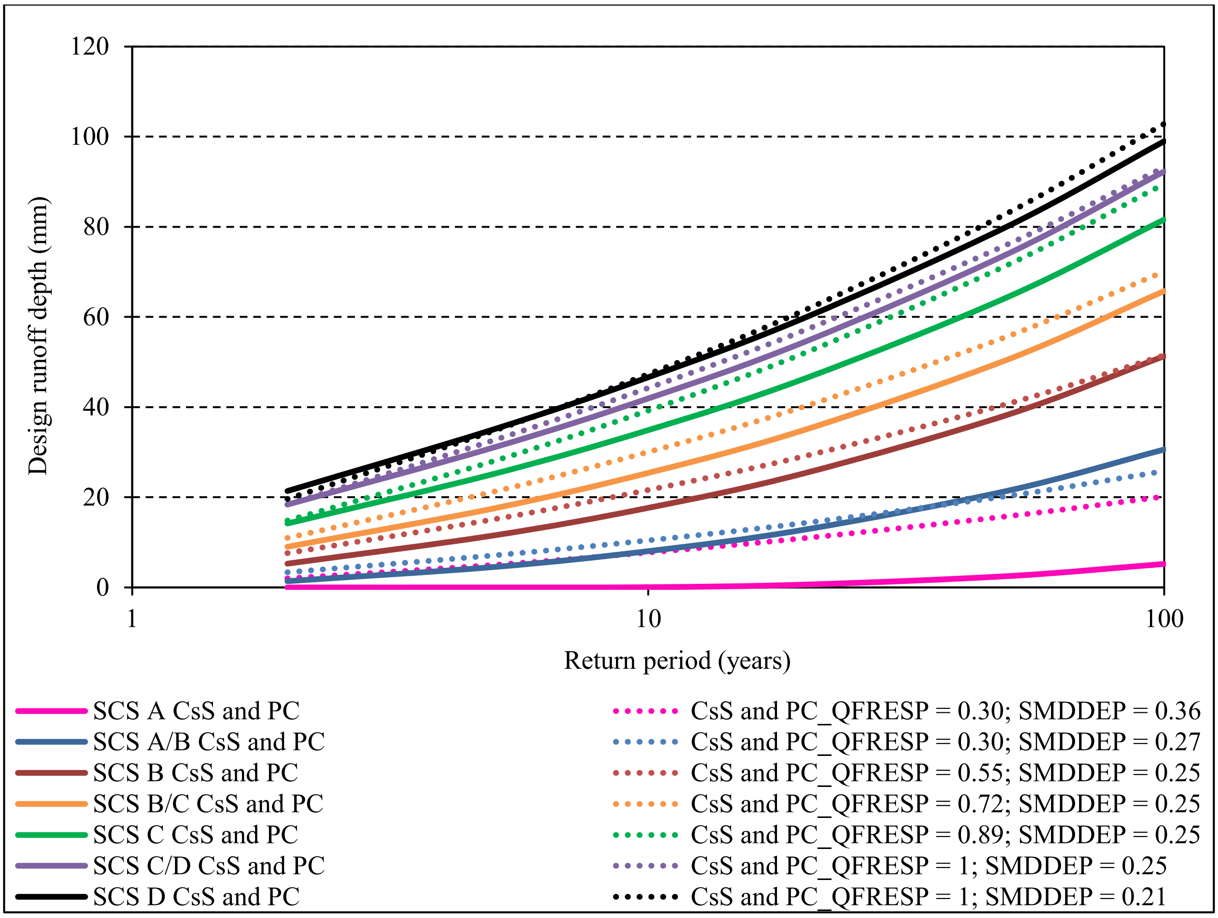
$$CN = 32.92(QFRESP) - 48.28(SMDDEP) + 63.91 \quad (7.3)$$

In addition, the following rules were determined for SCS-SA soil group C/D (Table 7.12). Similarly the rules are similar to those derived previously, however, in this case the CN ranges and prediction equation are quite different.

Table 7.12 Rules developed to determine *QFRESP* and *SMDDEP* values for CNs corresponding to SCS-SA soil group C/D

Rules	**CN 57 - 62**	**CN 62 - 85**	**CN > 85**
	***QFRESP* = 0.3**	***SMDDEP* = 0.25**	***QFRESP* = 1**
Input CN	62	85	85
Rearrange Equation 7.2 to solve for *SMDDEP or QFRESP*	*SMDDEP*	*QFRESP*	*SMDDEP*
Calculated value	0.24	1.01	0.25

Figure 7.27 compares the SCS-SA and *ACRU* design runoff volumes for a sugarcane land cover with Conservation Structures and Partial Cover, applying the revised rules summarised in Table 7.10 (all SCS-SA soil groups, excluding SCS-SA soil group C/D) and Table 7.12 (only SCS-SA soil group C/D).



*CsS and PC: Conservation Structures and Partial Cover

Figure 7.27 SCS-SA and *ACRU* design runoff comparisons for a sugarcane land cover, with Conservation Structures and Partial Cover for SCS-SA soil groups A to D, Quinary 4854, KZN, applying revised rules

The results from Figure 7.27 reveal that the unfavourable result identified in Figure 7.25, where the *ACRU* simulation results were larger for SCS-SA soil group C/D compared to SCS-SA soil group D, is corrected when applying the revised rules. Figure 7.28 further supports this observation showing that the average absolute difference between SCS-SA and *ACRU* simulation results for SCS-SA soil group C/D is far smaller when applying the revised rules compared to the initial rules implemented. In terms of the remaining SCS-SA soil groups, the revised rules had a negligible influence on the results, however, in some cases there was a slight increase in the absolute differences *e.g.* SCS-SA soil groups B/C, C and D. Ultimately, however, the revised rules have restored the trend of increasing runoff from SCS-SA soil groups A to D and comparable results between the SCS-SA and *ACRU* models have been presented. The average absolute differences obtained for a veld in good condition have also been included in Figure 7.28 as a reference for comparison, *i.e.* it is seen that although the sugarcane results are comparable, when applying the derived rules, they are as expected not as comparable as the results obtained through calibration for a veld in good condition. The findings therefore support the application of the rules and show that the rules may be used to reproduce design flood estimates in the *ACRU* model similar to those estimated in the SCS-SA model. Further testing of the approach and rules developed is required and recommended, however, these preliminary results have been extremely promising.

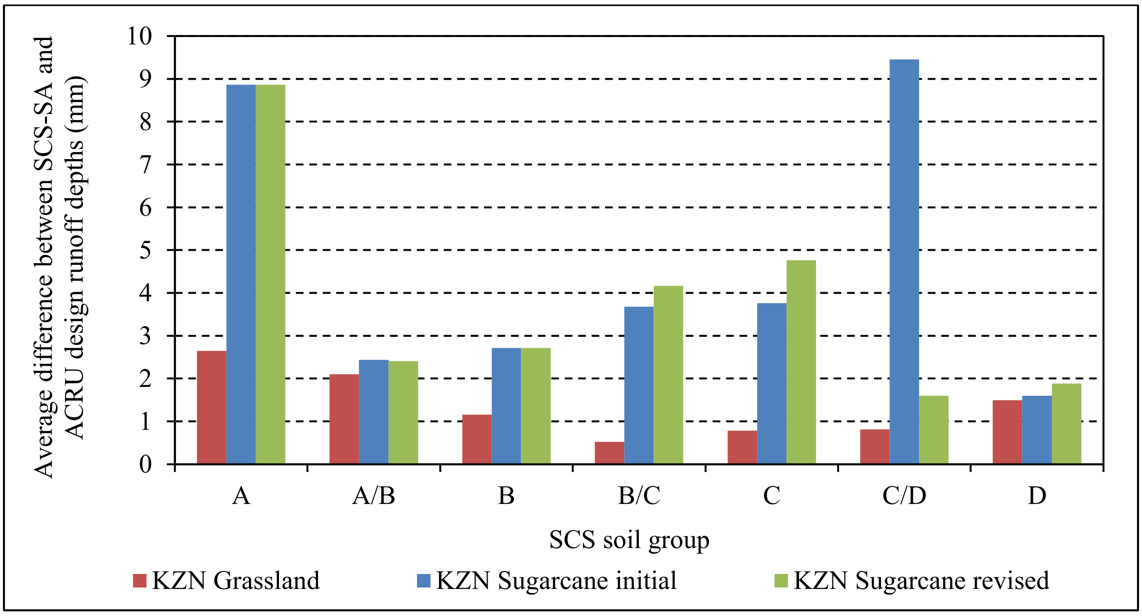


Figure 7.28 Average absolute difference between SCS-SA and *ACRU* design runoff simulations (averaged for the 2 – 100 year return periods) for a veld in good condition and a sugarcane land cover with Conservation Structures and Partial Cover (initial and revised results) in KZN for SCS-SA soil groups A to D

8. DISCUSSION AND CONCLUSIONS

Several severe flooding events across South Africa in recent years and the potential impacts of climate change have highlighted the need for updating and refining DFE methods used in South Africa. A review of DFE in South Africa has highlighted that approaches to DFE may be categorised into two groups: (i) analysis of observed flood peaks; and (ii) rainfall-runoff based methods. In terms of approaches based on the analysis of observed flood peaks, flood frequency analyses are commonly utilised, both at-site or regionalised. Flood frequency analysis has received increasing interest as it generally results in more reliable design estimates due to, *inter alia*, a greater representation of flood data being utilised from homogeneous regions. Other approaches based on the analysis of observed flood peaks such as Empirical methods, Flood Envelopes and the Run-hydrograph approach are also available, however, hydrologists and engineers are often required to estimate design floods for catchments without streamflow, or adequate streamflow, data. Therefore rainfall-runoff based techniques need to be utilised, since rainfall records are generally more numerous, accurate and spatially representative in comparison to streamflow records.

Rainfall-runoff techniques are divided into two groups, namely event-based approaches and continuous simulation. Historically event-based approaches such as the Rational method, Unit Hydrograph method and the SCS based approaches have been used. Extensive research has been undertaken in the past in the development of the SCS-SA adaptation of the SCS technique and the method has provided reasonable results. The success of the SCS-SA technique is largely attributed to the ability of the method to account for antecedent soil moisture conditions and the joint association of rainfall and runoff. The median condition and joint association methods account for the antecedent soil moisture conditions 30 days prior to large rainfall events. It is therefore argued that this attribute of the SCS-SA method led to the realisation of the potential for a CSM approach to DFE in South Africa. This leads on to the second rainfall-runoff based technique, CSM. In the review, the potential of the CSM approach to overcome many of the limitations of event-based approaches was highlighted, however, some challenges associated with the technique were also identified, including, *inter alia*, that the method is computationally demanding and requires extensive input information. With recent developments, however, in terms of computation and available technology, many of the challenges associated with CSM may be overcome. Therefore, following strong evidence of the potential of CSM in DFE, within the literature, the topic was reviewed in more detail.

To further justify continued development into a CSM approach in South Africa, it was necessary to review contemporary international literature to identify if the same trends towards CSM in DFE are also evident internationally. The review highlighted that the potential for CSM in DFE has also been identified internationally, with several continuous simulation models being developed and tested in several countries including, but not restricted to, the USA, Australia and Europe. The next step taken was to review what work on CSM for DFE had been undertaken in South Africa to date. It was found that several studies obtained reasonable results using the locally developed daily time-step *ACRU* agrohydrological model. Smithers *et al.* (2007) and Smithers *et al.* (2013), however, identified several aspects of the *ACRU* CSM approach that require further development and refinement.

From the literature reviewed, it was highlighted that rainfall, land cover and soils information are critically important inputs to the *ACRU* model and are thus in the greatest need of refinement and development. Rainfall is the driver of the hydrological cycle and hence the *ACRU* model, therefore updated and extended rainfall records will extend the period of simulated output by the *ACRU* model. The importance of extended rainfall records was also highlighted by Smithers *et al.* (2013). The updating of rainfall records up to the current date, *i.e.* beyond the year 2000, is therefore identified as a research need. This, however, is a challenging task and was not within the scope of this research project.

Following a review on hydrological modelling and the links and similarities between the SCS-SA and *ACRU* models, it was identified that in terms of land cover information, the land cover classification used in the SCS-SA model accounts for different land management practices and hydrological conditions, which are not accounted for in the current *ACRU* land cover classification, as well as the standardised hierarchical classification system being developed by Clark (2014). Since the CNs used in the original SCS model were derived from observations, and the SCS-SA model is an accepted method of DFE in small catchments in South Africa (Schmidt and Schulze, 1987a; Schulze *et al.*, 2004; SANRAL, 2013), it was assumed in this study that the design volumes simulated by the SCS-SA model are reasonable, and that the relative changes in design volumes simulated by the SCS-SA model as a consequence of changes in land management practice or condition are also reasonable.

Based on these assumptions, the general approach to the study was to investigate how design volumes simulated by the SCS-SA model for various land management practices or conditions could be simulated by the *ACRU* model, and to derive classes in the *ACRU* hierarchical classification for land management practice and hydrological condition. Therefore, design runoff volumes and changes in design runoff volumes, for different management practices and hydrological conditions, as simulated by the SCS-SA model, were used as a substitute for observed data, *i.e.* as a reference, to achieve similar design runoff volumes and changes in design volumes in the *ACRU* model. This was achieved by adjusting relevant variables in the *ACRU* model to represent the change in management practice or hydrological condition, as represented in the SCS-SA model. It is important to note that, as a starting point, the current state of the art information derived from continuous research and the expert knowledge of Schulze (2013) was used as the initial input into the *ACRU* model and adjustments were made from these expert opinions on how to simulate management practices in the *ACRU* model.

To achieve the above, the first step taken was to investigate the correlation between the soil representation in the SCS-SA and *ACRU* models, recalling that: (i) in the SCS-SA model soils are integrated into a single runoff response index, *i.e.* the CN which accounts for the land cover, land management practice and antecedent soil moisture; and (ii) in the *ACRU* model, soils are represented explicitly and in detail, with the land cover and management conditions being modelled by varying the input soils and land cover variables which control the various hydrological process, *e.g.* interception of rainfall by vegetation, vegetation crop coefficients and the initial abstraction of rainfall to account for impacts of surface conditions on infiltration.

Initially three attempts were made to link SCS-SA soil groups to soil textural properties in the *ACRU* model. The first attempt involved analysis of the soil textural properties and SCS-SA soil groups assigned per Land Type by Schulze (2012). The analysis did not produce comparable results between the SCS-SA and *ACRU* models. The following rules were developed in order to quantify how comparable the *ACRU* and SCS-SA results were to one another: (i) Highly comparable: the average absolute change ≤ 2 mm; (ii) Comparable: 2 mm < average absolute change ≤ 6mm; (iii) Poorly comparable: 6 mm < average absolute change ≤ 10mm; (iv) Incomparable: the average absolute change > 10 mm. Furthermore in terms of the first attempt, an inconsistent runoff trend was obtained for the *ACRU* simulations where runoff did not increase consistently from SCS-SA soil group A to C/D, *i.e.* with no SCS-SA soil group D obtainable for the Land Type approach. The second attempt was similar to the first attempt, however, in this case soil textural properties were averaged for each SCS-SA soil groups from the Binomial Soil Classification to represent each SCS-SA soil group in the *ACRU* model. Inconsistent runoff trends were also identified for this attempt. In addition the analysis, although an improvement on the first attempt, did not produce comparable results between the SCS-SA and *ACRU* models. The third attempt involved arranging design runoff volumes output by the *ACRU* model in order of increasing runoff, for several of the default soil textural classes available as input into the model, and through calibration assigning a soil textural class to each SCS-SA soil group. Through this approach, the inconsistencies in the runoff trends were overcome, however, the SCS-SA and *ACRU* runoff comparisons were once again poor. Therefore, all three approaches failed to represent the large range in runoff volumes obtained for SCS-SA soil groups A – D, but specifically the low runoff producing soils, SCS-SA soil groups A – B. The results revealed that correlation of SCS-SA soil groups to *ACRU* soil textural properties alone is not adequate.

This lead on to a sensitivity analysis of *ACRU* input variables related to soil properties, as well as land cover information, in order to identify which *ACRU* input variables are most sensitive in terms of design runoff volumes. The sensitivity analysis identified two model variables that are particularly sensitive in terms of design runoff estimates. The variables are: (i) the *QFRESP* coefficient, which partitions stormflow generated from a rainfall event into a same day response fraction and a subsequent delayed stormflow response; and (ii) the *SMDDEP*, which determines the critical response depth of the soil. These variables were then used to investigate if they could be calibrated to represent SCS-SA soil groups/CNs. For selected land cover classes, a calibration procedure was implemented to identify the most appropriate *QFRESP* and *SMDDEP* combination to represent each SCS-SA soil group. A veld land cover and a maize/row crop were initially investigated for a hypothetical 1km^2 catchment in KZN. The design runoff results between the SCS-SA and *ACRU* models, for this calibration procedure, were significantly comparable. The calibrated *QFRESP* and *SMDDEP* variables found to represent SCS-SA soil groups best for a veld land cover were then directly transferred and used to estimate design runoff volumes in Mpumalanga, to confirm that the calibrated values may be consistently applied at a different geographical location. This was repeated for the Western Cape where a veld land cover was again tested for consistency. An additional calibration, however, was conducted for a wheat/small grain land cover in the

Western Cape, *i.e.* as an equivalent to maize in KZN. The calibrated results were once again significantly comparable. A statistical analysis was consequently performed to identify any trends between SCS-SA CNs and *ACRU QFRESP* and *SMDDEP* variables. A multiple linear regression analysis (Table 7.4), performed in Microsoft Excel, revealed a strong linear relationship between SCS-SA CNs and the *QFRESP* and *SMDDEP* values calibrated to represent SCS-SA soil groups/CNs best. The regression results were then used to assist in the analysis of the design runoff results from a sugarcane land cover.

Some difficulty in simulating design runoff for a sugarcane land cover in the *ACRU* model was encountered. The main reason for this being that the runoff generated from sugarcane in the SCS-SA model is characteristically very low. Reproducing these low runoff volumes in the *ACRU* model and attempting to fit an LP-III distribution to the data, however, is challenging due to the following reasons. For the smaller design rainfall events no, or very low, runoff volumes are generated. Consequently, when attempting to determine the LP-III extreme value distribution from the AMS, there are zero or near zero values within the AMS, which means that the LP-III distribution cannot be fitted to the AMS which contains zero values. Furthermore, very low or near zero values strongly skew the data, which results in a distribution that fits the AMS poorly. Therefore some rules had to be developed regarding how a sugarcane land cover should be represented in the *ACRU* model, *i.e.* what values should be assigned to certain input variables. The multiple linear regression analysis obtained from the above calibration procedure of *QFRESP* and *SMDDEP* against CNs for a veld, maize and wheat land cover was then used to develop a regression equation (Equation 7.1 and Table 7.8) to determine *QFRESP* and *SMDDEP* values applicable to represent certain CN ranges, for a sugarcane land cover in the *ACRU* model. These rules and the regression equation were then used to simulate runoff volumes in the *ACRU* model corresponding to runoff volumes simulated in the SCS-SA model for a specific sugarcane land cover class.

The results from the *ACRU* model were compared to those from the SCS-SA model and a discrepancy in the results was identified for SCS-SA soil group C/D (Figure 7.25 and Figure 7.26). It was discovered that the discrepancy related to SCS-SA soil group C/D was as a result of the anomalous soil textural properties assigned to SCS-SA soil group C/D, through the Binomial approach. Subsequently, the results for a C/D soil were separated from the remaining SCS-SA soil groups and two separate multiple linear regression analyses were performed on: (i) all SCS-SA soil groups excluding SCS-SA soil group C/D (Table 7.9); and

(ii) SCS-SA soil group C/D alone (Table 7.11). A revised regression equation and rules were then developed for the former (Equation 7.2 and Table 7.10) and the latter (Equation 7.3 and Table 7.12). This corrected the discrepancy in the results and produced comparable results between the *ACRU* and SCS-SA models (Figure 7.27 and Figure 7.28). Table 8.1 below summarises the preliminary rules and equations that are recommended for use in order to obtain design runoff volumes using the *ACRU* model with results and trends similar to those simulated by the SCS-SA model, based on the results and findings presented in this document.

The rules and equations summarised in Table 8.1 are best preliminary estimates based on the results obtained in this research. Further investigation and validation of the approach however, is needed and recommended, including the analysis of additional land uses/land cover classes, further independent verification at different geographical locations as well as verification of the simulated results against observed data. These, as well as several additional aspects associated with CSM for DFE, are deemed to be in need of development and improvement and are discussed in the recommendations chapter to follow.

Table 8.1 Summary table of preliminary rules to be used when attempting to obtain design runoff volumes and trends in the *ACRU* model similar to those simulated by the SCS-SA model

Soil Textural Properties to Represent SCS-SA Soil Groups A - D							
Parameter	**A soils**	**A/B soils**	**B soils**	**B/C soils**	**C soils**	**C/D soils**	**D soils**
PWP ($m.m^{-1}$)	0.096	0.112	0.126	0.142	0.153	0.209	0.153
DUL ($m.m^{-1}$)	0.181	0.2	0.217	0.233	0.248	0.308	0.246
PO ($m.m^{-1}$)	0.434	0.436	0.434	0.43	0.424	0.431	0.435
ABRESP/BFRESP	0.648	0.61	0.582	0.554	0.518	0.403	0.517
General Rules							
In the simulations performed the following soil depths were used in the *ACRU* model; A horizon: 0.25m, B horizon: 0.50m. The climate information of the specific quinary catchment in which simulations were being performed was used (taken from the QCD).							

Table 8.1 Continued

Land cover Class	Rules to Represent SCS-SA Land cover Classes in *ACRU*
Veld/grassland land cover in Fair condition	Use the default input information from the QCD for the prevailing natural land cover class (Acocks, 1988) assigned to the quinary catchment in which the *ACRU* model is applied
Veld/grassland land cover in Poor condition	Make the following changes to the default input information from the QCD for the prevailing natural land cover class (Acocks, 1988) assigned to the quinary catchment in which the *ACRU* model is applied (Schulze, 2013): (i) *CAY* reduced by a factor of 1.4, but *CAY* values not allowed to drop below 0.2 in any month; (ii) *VEGINT* reduced by 50%; (iii) *COIAM* values for summer rainfall regions being 0.10 for the months November to March, 0.15 for April, May and October and 0.20 for months June to September, while in the winter / all year rainfall areas *COIAM* values reduced to 0.20; and (iv) *PCSUCO* reduced to 10% for all months.
Veld/grassland land cover in Good condition	Make the following changes to the default input information from the QCD for the prevailing natural land cover class (Acocks, 1988) assigned to the quinary catchment in which the *ACRU* model is applied: (i) *CAY* increased by a factor of 1.2 for all months; (ii) *VEGINT* increased by 25% for all months.
Row crop/Maize land cover in Good condition	Use the default *ACRU* model input values for a general maize crop planted in November, COMPOVEG crop number 3120102.
Small grain/Wheat land cover in Good condition	Use the default *ACRU* model input values for a general wheat crop planted in June, COMPOVEG crop number 3020204.
Row crop/Maize land cover in Poor condition or Small grain/Wheat land cover in Poor condition	Make the following changes to the default *ACRU* model input values for a general maize crop planted in November, COMPOVEG crop number 3120102 or a general wheat crop planted in June, COMPOVEG crop number 3020204: (i) *CAY* reduced by 10%, but *CAY* values not allowed to drop below 0.2 in any month; (ii) *VEGINT* reduced by 20% in all months
Sugarcane land cover	Use the default *ACRU* model input values for a general sugarcane crop, COMPOVEG crop number 5200704. Change the *COIAM* to values equivalent to those of the general maize crop, COMPOVEG crop number 3120102.

Table 8.1 Continued

Determining *QFRESP* and *SMDDEP* Values to Represent SCS-SA Soil Groups in *ACRU*	
All SCS-SA soil groups, excluding SCS-SA soil group C/D	In addition to the conditions listed above, for each land cover class Equation 7.2 and the rules presented in Table 7.10 should be used to estimate the appropriate *QFRESP* and *SMDDEP* values corresponding to the CN value representative of the SCS-SA soil group, land cover class, land management practice and hydrological condition selected.
SCS-SA soil group C/D only	In addition to the conditions listed above, for each land cover class Equation 7.3 and the rules presented in Table 7.12 should be used to estimate the appropriate *QFRESP* and *SMDDEP* values corresponding to the CN value assigned to SCS-SA soil group C/D for the selected land cover class, land management practice and hydrological condition.

9. RECOMMENDATIONS

As stated in the previous chapter, further investigation and validation of the revised parameterisation approach for the *ACRU* model when used for DFE is strongly recommended and is elaborated on in the following sections.

9.1 *ACRU* Parameterisation Approach

The rules and equations summarised in Table 8.1 were identified as best preliminary estimates based on the results obtained in this study. The derived rules and equations, however, were only applied to one land cover, *i.e.* sugarcane, within a single location that was used in the development of the rules. Further independent testing of the derived rules and equations is therefore essential to validate their applicability. This can only be achieved by assessing the performance of the rules and equations for all the land cover classes investigated at various independent locations with contrasting climatic conditions. It is also important to note that in this study, only four land cover classes within the SCS-SA classification were investigated, namely a veld/grassland land cover, a row crop/maize land cover, a wheat/small grain land cover, and a sugarcane land cover. The SCS-SA land cover classification, however, comprises of thirteen land cover classes in total. Therefore there are an additional nine land cover classes that were not investigated. Consequently there is a need for further research to assess if these land cover classes may also be represented in the *ACRU* model through the *ACRU* parameterisation approach. Prior to further investigation with additional land cover classes and validation of the current land cover classes and associated rules and equations, it is essential to validate the simulated design runoff volumes obtained from the *ACRU* model in this study against observed data. This is critically needed to assess if the *ACRU* parameterisation approach produces simulation results comparable to actual observed data. This needs to be assessed first since the *ACRU* parameterisation approach becomes redundant if the method does not produce simulation results comparable to actual observed data. In order to achieve this, observed data needs to be sourced and analysed for suitability. This is identified as the critical next step that needs to be taken to validate the *ACRU* parameterisation approach and motivate for further development of the approach for different land uses/land cover classes. Furthermore, erroneous results were obtained when attempting to represent a CN value lower than 40 in the ACRU model. This also requires further investigation in future research.

This study has identified the links between the SCS-SA and *ACRU* models and an approach was developed to represent SCS-SA soil groups, hydrological conditions and land management practices in the *ACRU* model for selected land cover classes. In reality, however, the land cover classes in the SCS-SA classification and the *ACRU* hierarchical classification do not cover all the land uses and land cover classes currently found or cultivated within South Africa. In addition, the Quaternary and Quinary Catchments Databases have been assigned default land cover information based on the Acocks (1988) natural land cover map. In the case of DFE, however, current land cover information is needed to accurately estimate design floods. The following section subsequently discusses the issue of updating land cover information.

9.2 Updating Land Cover Information

It has been highlighted that the Quaternary and Quinary Catchments Databases have been assigned default land cover information based on the Acocks (1988) natural land cover map. Land cover is vitally important since it directly influences a catchment's response to rainfall and runoff. Clark (2014) identifies that the National Land Cover dataset for 2000 (NLC, 2000) is the most recent comprehensive national dataset of actual land cover in South Africa, which classifies land cover into 49 different classes. Updated land cover information for certain provinces, however, as described by The South African National Biodiversity Institute (SANBI), are available (SANBI, 2009). SANBI attempted to update the NLC (2000) dataset with recent provincial land cover information, as well as information from other sources where it was available, *e.g.* such as the ESKOM SPOT building count and informal settlements, as detailed in SANBI (2009), with the NLC (2000) dataset remaining as a "baseline" where updated information was not available. SANBI, however, simplified the 49 classes of the NLC (2000) into just eight classes due to the different land cover classification procedures used by the different provinces and therefore grouped all classifications into one of the eight classes defined by SANBI (2009). As highlighted by Clark (2014), this makes the SANBI (2009) national land cover map unsuitable for representing the detailed hydrological responses from the variable land cover within these classes in a catchment. As a result, Clark

(2014) is currently developing a standardised land cover/land use hierarchical classification system and classes that will accommodate the classifications used by various sources. The first step was to ensure that the 49 classes of the NLC (2000) were covered by the standard classification. Furthermore, default values for each land cover class also needed to be assigned for input into the *ACRU* model. To date, the standard classification of Clark (2014) covers all 49 classes of the NLC (2000) and initial default values for each class have been assigned based on data from COMPOVEG. Some of the *ARCU* variables assigned, however, are in need of revision and verification which is an ongoing process, achieved through research. Although the NLC (2000) is a reasonable baseline land cover, the information is relatively outdated and therefore obtaining updated land cover information from as many sources as possible is necessary. Based on this realisation, the sources of some of the updated provincial land cover datasets, as mentioned by SANBI (2009), and where they may be obtained, was investigated. After consultation with Mark Thompson from GeoTerraImage, an independent company specialising in geo-spatial technologies, a list of updated provincial land cover information currently available and where it may be sourced was provided (Thompson, 2014). The list provided is included in Table 9.1.

Table 9.1 Updated provincial land cover information available (Thompson, 2014)

20m SPOT5 2011 updated KZN provincial land cover dataset
10m SPOT5 2009 Free State provincial land cover dataset
10m SPOT5 2009 Limpopo provincial land cover dataset
10m SPOT5 2010 North West provincial land cover dataset
Vector based 2010 limited class land cover dataset of the Mpumalanga province

Subsequently, a copy of each of the datasets was requested. The Mpumalanga, KZN and Free State land cover datasets were obtained. The Mpumalanga provincial land cover dataset, being a limited class land cover dataset, only has eight classes and therefore is unsuitable. The KZN land cover is, however, very suitable and similar to the NLC (2000) with 47 classes. The previous KZN land cover dataset (2008) has the same classes as the updated 2011 dataset and Clark (2014) has assigned each of the KZN land cover classes to the standard hierarchical classification system. The Free State land cover dataset covers 84 classes, which similarly may be assigned to the classes of the standardised classification system developed by Clark (2014). It is therefore recommended that the QCD be updated with the aforementioned land cover maps representing the actual land cover within each quinary. This, however, is a challenging task since suitable *ACRU* variables for these land uses/land cover classes need to be estimated. This may possibly be achieved using a similar approach utilised by Schulze (2004) where climatic information including *inter alia*, heat units, frost days and MAP, were used to derive *ACRU* inputs for the Acocks (1988) baseline land cover currently utilised in the QCD. Another, possibly more accurate, alternative would be to obtain observed data from such new crops to determine *ACRU* inputs. This option, however, is time consuming and costly. Updating land cover information, however, is an important research need and requires further investigation.

In addition to updating land cover information an important investigation that was not addressed in this study is the estimation of peak discharge, which will be elaborated on in the section to follow.

9.3 Peak Discharge

Estimating runoff volumes was identified as a crucial first step in the analysis of design floods, however, the next step needed is to extend the analysis to the estimation of peak discharge. Peak discharges need to be simulated in addition to runoff volumes in the *ACRU* parameterisation approach and the simulated peak discharges need to be compared against observed peaks. Thereby the validity of the *ACRU* parameterisation approach with regard to estimating both runoff volumes and peak discharges is tested.

Estimating peak discharge, however, remains a challenging task largely because of the difficulty in accurately determining the catchment lag and additionally disaggregating daily rainfall volumes into sub-daily quantities. In the SCS-SA and *ACRU* models, complete storm hydrographs are generated by superpositioning of incremental triangular unit hydrographs according to the distribution of stormflow over time, as determined from the time distribution of rainfall intensity and the stormflow response characteristics of the catchment (Schulze *et al.*, 1992). One-day design rainfall depths are used to compute total stormflow depths. The one-day design rainfall depth, however, is distributed over time through the course of the day. The time distribution of rainfall depends on the typical rainfall mechanisms that produce design storms. In the original SCS method developed in the USA, two rainfall distributions were introduced to describe two different rainfall mechanisms, *i.e.* intensities (Schmidt and Schulze, 1987a).

In the SCS-SA adaptation, however, this was found to be insufficient and therefore four general rainfall distribution types were developed for South Africa to account for rainfall intensity, after analysis of rainfall data from recording raingauges across the country (Weddepohl, 1988 cited in Schmidt and Schulze, 1987). Synthetic time distribution curves were developed for each of the four distributions, namely Types 1, 2, 3 and 4. Using the synthetic rainfall distribution curves and the data from recording raingauges across the country, regions in South Africa were divided-up according to each of the four distributions. Ultimately rainfall distribution zones were mapped for South Africa (Schmidt and Schulze, 1987a). Therefore, by using the appropriate synthetic distribution, and a simple relationship developed by Schmidt and Schulze (1987) relating short-duration design rainfall to one-day design rainfall for the respective distribution type, appropriate design rainfall intensities can be applied to any catchment, regardless of the response time of the catchment (Schulze, 1992). Therefore, the appropriate synthetic distribution, *i.e.* rainfall intensity, for all catchments that fall within the distribution zone may be applied, regardless of the response time of individual catchments (Schulze *et al.*, 1992). The same outdated procedure is also implemented in the *ACRU* model (Schulze, 1995).

Knoesen (2005), however, realising the need to improve on the method currently used, developed and evaluated a new method to disaggregate daily rainfall into hourly totals in South Africa. This was achieved using a regionalised semi-stochastic daily rainfall disaggregation model developed by Knoesen (2005). The model performed reasonably well with some suggestions to further refine certain aspects of the model (Smithers *et al.*, 2013). Therefore an additional research need is identified to further investigate and expand on the findings of Knoesen (2005) to improve peak discharge estimates and hydrograph shapes. Gericke (2011), has proposed research into the estimation of catchment lag and it is hoped that these research results may be utilised and included in further analyses to further improve on the estimation of peak discharge. Until this research is complete, however, the Schmidt-Schulze lag equation used in the calculation of peak discharge is likely the most suitable method currently available. It should be noted, however, that the Schmidt-Schulze lag equation uses MAP as a surrogate for land cover density and soil water holding capacity. This implies that potentially erroneous lag times could be estimated in catchments that have experienced major land cover changes or where the MAP represents that of a future climate. Some additional aspects, highlighted from the literature reviewed and which are in need of development, include improved methods to account for water abstractions and transfers between catchments and further work on the temporal distribution of rainfall.

9.4 Runoff Routing

When using a CSM approach, an additional aspect of DFE that needs improvement, is the routing of runoff volumes and peak discharges through catchments as floods cascade down from one catchment to another. Runoff routing generally requires river reach specific information. As identified in the literature reviewed, however, Tewolde (2005) and Tewolde and Smithers (2006) developed and assessed techniques for flood routing in ungauged catchments using streamflow data from the Thukela catchment. The results showed that the Muskingum-Cunge method may be used to route floods in ungauged catchments within the Thukela catchment, with parameters estimated using empirical relationships (Smithers *et al.*, 2013). Further investigation into runoff routing techniques is an additional aspect that is recommended in further research.

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