# DEVELOPMENT AND ASSESSMENT OF AN IMPROVED CONTINUOUS SIMULATION MODELLING SYSTEM FOR DESIGN FLOOD ESTIMATION IN SOUTH AFRICA USING THE *ACRU* MODEL

by

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**Submitted in fulfilment of the academic requirements for the degree of**
**Doctor of Philosophy**

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# PREFACE

The research contained in this thesis was completed by the candidate while based in the Centre for Water Resources Research, School of Agricultural, Earth and Environmental Sciences, College of Agriculture, Engineering and Science, University of KwaZulu-Natal, Pietermaritzburg, South Africa. The research was financially supported by the University of KwaZulu-Natal and the National Research Foundation.

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

Signed: Professor JC Smithers

Date: 17 September 2019

D J Clark

Signed: Dr DJ Clark

Date: 17 September 2019

# DECLARATION 1: PLAGIARISM

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

(a) The research reported in this thesis, except where otherwise indicated or acknowledged, is my original work.

(b) This thesis has not been submitted in full or in part for any degree or examination to any other university.

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# DECLARATION 2: PUBLICATIONS

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

**Chapter 2**

Rowe, TJ* and Smithers, JC. 2018. Review: Continuous simulation modelling for design flood estimation – a South African perspective and recommendations. *Water SA 44* (4): 691-705. DOI: 10.4314/wsa.v44i4.18.

This paper is based on a literature review I conducted. I reviewed, summarised and synthesised the literature and wrote the paper. My co-author, Professor Jeff Smithers, provided guidance and reviewed the paper prior to submission for publication.

Signed: TJ Rowe

Date: 17 September 2019

# ABSTRACT

An estimate of the risk associated with flood events is required to adequately design hydraulic structures and limit negative socio-economic impacts as a result of floods. The methods used to estimate design floods in South Africa are outdated and are in need of revision. A National Flood Studies Programme (NFSP) has recently been initiated by Smithers *et al.* (2016) to overhaul Design Flood Estimation (DFE) procedures in South Africa. One of the recommendations of the NFSP is development and assessment of a Continuous Simulation Modelling (CSM) approach to DFE. Consequently, the aim of this study is to further develop and assess the performance of an improved comprehensive CSM system, to consistently and reliably estimate design flood discharges in small catchments (0 - 100 km$^2$) in South Africa using the *ACRU* model. In the development of the approach a strong emphasis has been placed on ease of use from a practitioner's point of view. The aim is achieved through several specific objectives as summarised below.

The first objective was to review CSM approaches applied locally and internationally for DFE, in order to identify research gaps and guide the development of an improved national CSM system for DFE in South Africa. The review culminates with a list of recommendations and steps required to develop and adopt a CSM approach for DFE in practice. The first critical step identified and required was the development of a comprehensive CSM system using the *ACRU* model (Schulze, 1995). This included: the structure of the system and how to implement the system, an enhanced land cover and soils classification to apply with the system and default input information and databases to use with the system.

The second objective addresses the recommendations made from the literature review, where a comprehensive CSM system for DFE using the *ACRU* model is developed and described in detail. Based on similarities identified between the *ACRU* (Schulze, 1995) and SCS-SA models (Schmidt and Schulze, 1987a), as well as the fact that the SCS-SA model is relatively simple and widely applied in practice, the CSM system was adapted to be consistent with the land cover classification used in the SCS-SA model. This included the incorporation of a methodology and rules, developed by Rowe (2015), to represent land management practices and hydrological conditions within the *ACRU* model. The development of this comprehensive CSM system with default national scale inputs and land cover classifications contributes to new

knowledge on how to package a CSM system for DFE in South Africa.

The third objective focuses on the assessment and verification of the CSM system developed, using observed data. Through the verifications and assessments performed an inconsistency between daily simulated stormflow volumes and the volume of stormflow used in the daily stormflow peak discharge equation was identified. Therefore, a revision, which is more conceptually correct than the current assumption that all stormflow generated from an event contributes to the peak discharge on the day, was applied to the fraction of the simulated daily stormflow used in the peak discharge equation. This corrected the inconsistency and significantly improved the results, thereby providing an improved methodology to more accurately estimate peak discharges in the *ACRU* model than had hitherto been the case.

Despite the improvement in the results, a general over-simulation of peak discharges was still evident. Consequently, further investigation of the *ACRU* stormflow peak discharge computations was performed in order to identify which approach provides the most satisfactory results (Objective 4). This included a performance assessment of both the SCS single Unit Hydrograph (UH) approach and the incremental UH approach. The performance of each approach was assessed using both estimated parameters and parameters derived from observed data. These parameters include stormflow volumes, catchment lag times, and the distribution of daily rainfall, where applicable, to each approach. Comparison of the results from the two approaches indicated that more accurate results are obtained when applying the incremental UH approach, when using both estimated or observed parameter inputs. In terms of the incremental UH approach, it was identified that the approach is more sensitive to the use of synthetic daily rainfall distributions compared to estimated lag times. Based on the results obtained new knowledge and additional research gaps related to: (i) improved estimation of the distribution of daily rainfall within the *ACRU* model, (ii) links between the distribution of daily rainfall and catchment lag time, and (iii) the need to further verify and possibly recalibrate *CN*s for South Africa were identified.

The fifth objective addressed is an assessment of the impact of model configuration on the performance of the *ACRU* CSM system developed, in order to propose a final CSM system for DFE in South Africa. Results when using site-specific land cover and soils information are compared to those obtained when different sources of input information are used, such as the national land cover and soils maps developed for the entire country. The results when using

these default national datasets were not particularly good, however recommendations are made to improve on the results. In addition, the most appropriate current databases to use with the CSM system are defined, providing users with the most appropriate default information currently available to use in the absence of site-specific information.

The last objective addressed was a comparison of the performance of the final *ACRU* CSM system proposed in this study to that of the widely applied SCS-SA model and associated approaches, when using the same input information. Ultimately, the final *ACRU* CSM system proposed provides results that are superior to those from the SCS-SA model and associated approaches. In addition, several advantages of the *ACRU* CSM system over the traditional SCS-SA approaches were identified. Recommendations were, however, made to improve on the CSM system developed in this study and to use the results to update the SCS-SA model. New knowledge on the performance of the SCS-SA model and its associated approaches compared to that of the comprehensive CSM system developed for South Africa is therefore provided in this study.

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| **Acronym / *Variable*** | **Description** |
|---|---|
| *ABRESP* | Fraction of soil water above FC1 that drains from the topsoil into the subsoil |
| *ACRU* | Agricultural Catchments Research Unit |
| AMS | Annual Maximum Series |
| ARR | Australian Rainfall and Runoff |
| AWBM | Australian Water Balance Model |
| *BFRESP* | Fraction of soil water above FC2 that drains from the subsoil into the intermediate groundwater zone |
| $BFIq_p$ | Baseflow and interflow contribution to total daily peak discharge |
| $BFq_p$ | Baseflow contribution to total daily peak discharge |
| $BF_i$ | Simulated baseflow for the current day |
| $BF_{(i-1)}$ | Simulated baseflow for the previous day |
| *CN* | Curve Number |
| *CN-II* | Initial Catchment CN |
| $CN_p$ | Predicted *CN V*alues |
| *COIAM* (*ACRU*) | Coefficient of Initial Abstraction |
| *c* (SCS-SA) | Loss coefficient |
| COST | The European Cooperation in Science and Technology |
| CRCCH | Cooperative Research Centre for Catchment Hydrology |
| CS | Continuous Simulation |
| CSIR | Council for Scientific and Industrial Research |
| CSM | Continuous Simulation Modelling |
| CSS | Continuous Simulation System |
| CWRR | Centre for Water Resources Research |
| DE | Design Event |
| DEM | Digital Elevation Model |
| *DEPAHO* | Depth of the topsoil |
| *DEPBHO* | Depth of the subsoil |
| DFE | Design Flood Estimation |
| DHI | Danish Hydraulic Institute |
| DnQp | Design Peak Discharges |
| DnV | Design Streamflow Volumes |
| DWS | Department of Water and Sanitation |
| DyQp | Daily Peak Discharges |
| DyV | Daily Streamflow Volumes |
| EDF | *Electricité de France* |
| *FC1* | Field Capacity (topsoil) |
| *FC2* | Field Capacity (subsoil) |
| FEH | Flood Estimation Handbook |
| FFA | Flood Frequency Analysis |
| FFCs | Flood Frequency Curves |

| **Acronym / *Variable*** | **Description** |
|---|---|
| FSR | Flood Studies Report |
| GLUE | Generalised Likelihood Uncertainty Estimation |
| HEC-HMS | The Hydrologic Engineering Center – Hydrologic Modeling System |
| HEC-RAS | The Hydrologic Engineering Center – River Analysis System |
| HRUs | Hydrological Response Units |
| HSPF | Hydrologic Simulation Program Fortran |
| HYSIM | Hydrological Simulation Model |
| *I* | Interflow (*UQFLOW - UQFLOW OTD*) |
| JAM | Joint Association Method |
| JPV | Joint Peak-Volume |
| KZN | KwaZulu-Natal |
| MAP | Mean Annual Precipitation |
| MARE | Mean Absolute Relative Error |
| MCM | Median Condition Method |
| MISDc | *Modello Idrologico Semi-Distribuito in continuo* |
| MRE | Mean Relative Error |
| NDVI | Normalised Difference Vegetation Index |
| NERC | Natural Environment Research Council |
| NFSP | National Flood Studies Programme |
| NLC | National Land Cover |
| NSE | Nash Sutcliffe Efficiency |
| Obs Lag | Observed Catchment Lag Time |
| Obs Q | Observed Stormflow |
| Obs Rain | Observed Rainfall |
| PDM | Probability Distributed Model |
| *PO1* | Porosity (topsoil) |
| *PO2* | Porosity (subsoil) |
| POT | Peak Over Thresholds |
| *QFRESP* (QF) | Quick Flow Response Coefficient |
| Qp | Peak Discharge |
| *QPEAK* | Simulated Peak Discharge |
| Rain T3 | Synthetic Type 3 Rainfall Distribution |
| Rain T4 | Synthetic Type 4 Rainfall Distribution |
| ReFH | Revitalized Flood Hydrograph model |
| ReFH2 | Updated Revitalized Flood Hydrograph model |
| *RFL* | Observed Rainfall |
| RMSE | Root Mean Squared Error |
| RP | Return Period |
| RSQ ($R^2$) | Coefficient of Determination |
| *S* | Soil Water Deficit |
| S&S Lag | Schmidt and Schulze (1984) Estimated Catchment Lag Time |
| SAEON | South African Environmental Observation Network |
| SANRAL | The South Africa National Roads Agency Limited |
| SAWS | South African Weather Service |

| **Acronym / *Variable*** | **Description** |
|---|---|
| SBM | Fine Resolution Space-Time String-of-Beads Model |
| SCHADEX | *Simulation Climato-Hydrologique pourl'Appréciation des Débits EXtrêmes* |
| SCS | Soil Conservation Service |
| SCS-SA | South African Adaptation of the SCS Model |
| SF | Streamflow |
| SHE | *Systeme Hydrologique European* |
| SIRI | Soil and Irrigation Research Institute |
| *SMDDEP* (SM) | Critical Response Depth of the Soil |
| *STORMF* | Stormflow generated on the day of a rainfall event |
| *STORMF STORE* | Stormflow from the current day, plus delayed stormflow from previous days (conceptualised as interflow) |
| SWMM | Storm Water Management Model |
| TATE | Time-Area Topographic Extension |
| TOPMODEL | Topography-Based Model of Catchment Hydrology |
| $T_B$ | Base Time |
| $T_C$ | Time of Concentration |
| $T_L$ | Time Lag |
| $T_P$ | Time to Peak |
| *UBFLOW* | Simulated Baseflow |
| UH | Unit Hydrograph |
| UKZN | The University of KwaZulu-Natal |
| *UQFLOW* | Same Day Response Fraction (from the *STORMF STORE*) |
| *UQFLOW OTD* | *UQFLOW ON THE DAY* (Fraction of *STORMF* that is actually released on a particular day) |
| UN | United Nations |
| UNISDR | United Nations Office for Disaster Risk Reduction |
| USACE | The United States Army Corps of Engineers |
| USEPA | United States Environmental Protection Agency |
| *USFLOW* | Simulated Streamflow |
| *WP1* | Permanent Wilting Point (topsoil) |
| *WP2* | Permanent Wilting Point (subsoil) |
| WRA | Water Resource Associates |

# 1. INTRODUCTION

This chapter provides some background on Design Flood Estimation (DFE) in South Africa and the potential of a Continuous Simulation Modelling (CSM) approach to DFE and includes the rationale, justification and objectives of the research. An outline of the thesis structure is also provided.

## 1.1 Rationale

The assessment of flood risk by associating the magnitude of a flood event with a probability of exceedance or return period is the standard approach to Design Flood Estimation (DFE) in most countries (Smithers, 2012; Kang *et al.*, 2013). This is essential to the planning, prevention and control of the damaging effects of flooding to hydraulic infrastructure such as dams, bridges and culverts, and to development sites situated within floodplains (Lamb *et al.*, 2016).

Smithers (2012) and Smithers *et al.* (2013) categorise DFE techniques used in South Africa into two groups: (i) the analysis of observed flow data, and (ii) rainfall-runoff based methods, as shown in Figure 1.1.

Most of the methods depicted in Figure 1.1 were developed in the 1970s and 1980s with the resources and hydrological data available at the time. With the extended hydrological records currently available, advances in technology and knowledge, and a number of extreme events exceeding previous records, the need to update these methods has been well documented in the literature (Alexander, 2002; Smithers and Schulze, 2002; Görgens, 2007; Smithers, 2012; van Vuuren *et al.*, 2013). Consequently, a National Flood Studies Programme (NFSP), aimed at updating and modernising the various approaches to DFE used in South Africa, has recently been proposed and initiated (Smithers *et al.*, 2016).

Further motivation regarding the need to update these methods is identified by severe flooding events in recent years, experienced both in South Africa and internationally (Alexander, 2002; Smithers, 2012; UNISDR, 2015; FloodList, 2016). Furthermore, changes in both the intensity and frequency of extreme rainfall events have been documented, both locally and internationally, associated with climate change (Kruger, 2006; Hrachowitz *et al.*, 2013;

Kusangaya *et al.*, 2014; Du Plessis and Burger, 2015; Kruger and Nxumalo, 2017). The damages and loss of life caused by recent flooding, and the realisation of possibly increased rainfall variability in the future, further emphasise the need to update DFE techniques used in South Africa.

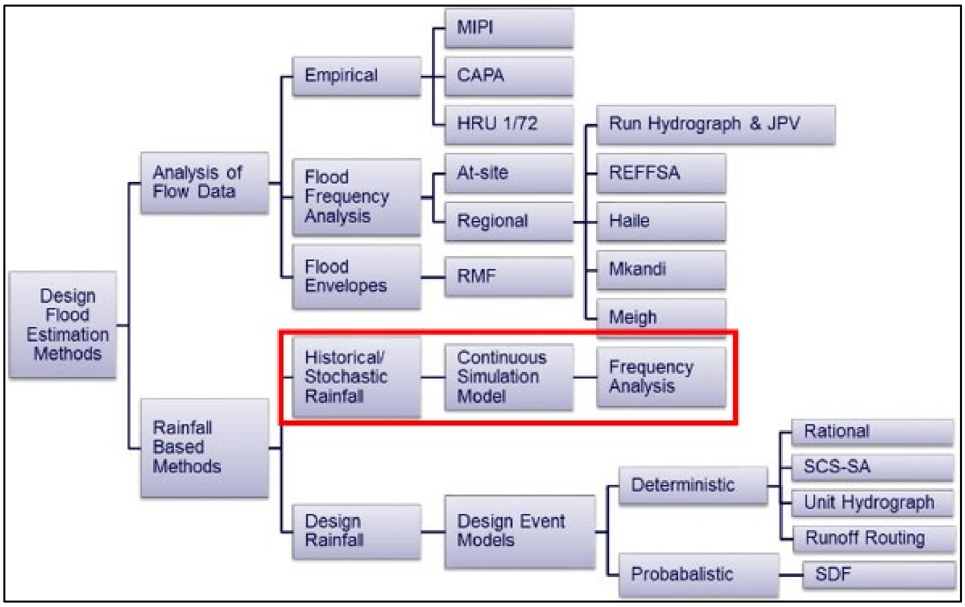

Figure 1.1 Design flood estimation methodologies within South Africa (after Smithers, 2012)

One of the recommendations contained in the plan for the NFSP is the development and assessment of a CSM approach to DFE, i.e. the rainfall-runoff approach encapsulated by a red border in Figure 1.1. Owing to the limited availability of streamflow data in South Africa, both in terms of number of gauges and record length, and/or errors and inconsistencies in the data, rainfall-runoff methods for DFE are often required and applied in preference to, or in combination with, methods based on the analysis of observed flow data. Rainfall records, on the other hand, are available from a denser network of gauges, are generally of better quality, and have longer records compared to streamflow data (Schulze, 1989; Smithers and Schulze, 2002; Smithers, 2012). The benefits of a CSM approach to DFE over traditional event-based rainfall-runoff techniques include, *inter alia*, the ability of the method to account for: (i) constant and changing catchment characteristics (e.g. land cover and climate), (ii) explicit representation of the impact of antecedent soil water conditions on runoff generation, and (iii) a more comprehensive representation of hydrological processes (Boughton and Droop, 2003; Brocca *et al.*, 2011; Smithers, 2012; Lamb *et al.*, 2016; Vogel, 2017). Lamb *et al.* (2016) state that a CSM approach to DFE is one of the most comprehensive methods available, with significant potential to address complicated problems and provide accurate design flood estimates. Therefore, based on the advantages of the CSM approach as alluded to above, the rationale for further development and assessment of a CSM approach for DFE in South Africa is evident.

## 1.2 Justification

A CSM approach, like many of the rainfall-runoff methods used in South Africa, is generally applicable and well suited to small catchments (0 - 100 km$^2$), but is however, not limited to this size range, for example a CSM approach to DFE was successfully applied in a pilot study in the 29 036 km$^2$ Thukela Catchment (Smithers *et al.*, 2013). According to Smithers *et al.* (2016), the majority of the catchments (55 %) for which design floods are required in South Africa are relatively small (< 15 km$^2$). In South Africa the daily time-step *ACRU* agrohydrological model (Schulze, 1995) has provided reasonable results for DFE in several pilot studies and investigations (Smithers *et al.*, 1997; Smithers *et al.*, 2001; Chetty and Smithers, 2005; Smithers *et al.*, 2007; Smithers *et al.*, 2013). The model is a physical conceptual model, since it is made up of idealised concepts, and is physically based, i.e. physical processes are explicitly represented (Schulze *et al.*, 1994). The model is not a parameter fitting or optimising model (Schulze *et al.*, 1994), and therefore parameters are not directly calibrated. Instead, parameters are assigned on the basis of physical catchment characteristics, as estimated or obtained in the field, and the performance of the model is verified against observed data (if available). Based on the verification results, specific parameters may be adjusted on the basis of a sound conceptual understanding of the hydrological processes within a catchment. Although promising results have been obtained applying a CSM approach to DFE, no comprehensive CSM methodology applicable at a national scale, such as is available for the event-based SCS-SA model, has been developed. The SCS-SA event-based method was adopted from the Soil Conservation Service (SCS, 1956; SCS, 1972) Curve Number (*CN*) method and adapted to South African conditions (Schmidt and Schulze, 1987a). The SCS-SA approach (Schmidt and Schulze, 1987a; Schulze *et al.*, 1992; Schulze *et al.*, 2004) is widely used in practice in South Africa for DFE (Smithers, 2012; SANRAL, 2013; Smithers *et al.*, 2016) and, like the CSM approach, is generally recommended for use on small catchments (0 - 100 km$^2$).

Rowe (2015) initiated preliminary investigations towards the development of a national scale CSM methodology for DFE within South Africa using the *ACRU* model. Rowe (2015), identified significant similarities and links between the SCS-SA and *ACRU* models, including the fact that both models use the SCS (1956) runoff equation, as represented in Equation 1.1 (Schulze, 1995), to estimate stormflow (i.e. surface and near-surface runoff).

$$Q = \frac{(P-cS)^2}{P+S(1-c)} \tag{1.1}$$

where, $Q$ is the stormflow depth [mm], $P$ is the gross daily precipitation amount [mm], $S$ is the potential maximum retention [mm] or the soil water deficit, and $c$ is a loss coefficient, represented as $c$ in the SCS-SA event-based model and referred to as the coefficient of initial abstraction (*COIAM*) in the *ACRU* continuous simulation model. Table 1.1 contains a summary of some important differences between the two models.

From Table 1.1, the main distinguishing difference between the SCS-SA and *ACRU* models is that the SCS-SA model is an event-based model and the *ACRU* model is a continuous simulation model. Therefore, the Return Period (RP) of the design stormflow (i.e. surface and near-surface runoff) simulated by the SCS-SA model is the same as the return period of the design rainfall used as input to the model. This, however, is not the case with the *ACRU* model, since an Extreme Value Analysis (EVA) is performed on simulated daily streamflow (i.e. both stormflow and baseflow) and therefore the joint association between rainfall, antecedent soil water and runoff is directly accounted for. As indicated above, as well as in Table 1.1, another important distinguishing attribute between the SCS-SA and *ACRU* models is that the SCS-SA model only simulates stormflow (i.e. surface and near-surface runoff) while the *ACRU* model simulates total streamflow (i.e. both stormflow and baseflow as detailed below). Therefore, it is important to note this distinction when referring to runoff from either the SCS-SA or *ACRU* model.

Table 1.1 Conceptual differences between the SCS-SA and *ACRU* model

| SCS-SA | *ACRU* |
|---|---|
| Event-based | Continuously simulates daily flows |
| Stormflow RP = Rainfall RP | Streamflow RP computed independently of Rainfall RP |
| *c* fixed | *COIAM* altered month-by-month |
| *S*<br>Single parameter:<br>Initial Curve Number (*CN-II*)<br><br>Soil water adjustment options<br>Final *CN* (MCM)<br>Design stormflow for selected *CN-II* (JAM) | *S*<br>Multiple time varying variables:<br>Soil parameters<br>Land cover/vegetation parameters<br><br>Additional parameters:<br>*SMDDEP*<br>*QFRESP* |

With respect to the SCS-SA model, an initial *CN* for average catchment conditions (*CN-II*), i.e. a stormflow response parameter defined for specific land cover and soil group classes, translated into an *S* value using Equation 1.2, is used in Equation 1.1 together with a design rainfall depth (*P*) and fixed default *c* value, to calculate a design stormflow depth (*Q*), with a return period equal to that of the design rainfall used.

$$S = \frac{(25400)}{CN} - 254 \tag{1.2}$$

*CN-II* may be adjusted to account for median antecedent catchment conditions applying the Median Condition Method (MCM). The method, however, still relies on this single catchment response parameter representing typical antecedent soil water conditions. The method was developed using results simulated by the *ACRU* model (Schmidt and Schulze, 1987a). A 30-day period prior to the five largest rainfall events for each year of record, was used to simulate the antecedent soil water prior to each event. A frequency analysis was then performed on the simulated antecedent soil water conditions and the median (50th), 20th and 80th percentiles recorded. Typically, the median condition (50th percentile) is then used to adjust *CN-II* for typical regional antecedent soil water conditions (Schmidt and Schulze, 1987a). Alternatively, the 20th (dry) or 80th (wet) percentile values may be used based on site-specific information and/or the potential impact associated with failure of the structure for which the design flood estimate is required (Schmidt and Schulze, 1987a), e.g. the 80th percentile value may be used to be more conservative in the design of a structure with high hazard potential.

An alternative to the above is the use of the joint probability approach, termed the Joint Association Method (JAM), where *CN-II* was adjusted for each of the five largest rainfall events in each year of record, based on the antecedent water conditions simulated for 30 days prior to each event using the *ACRU* model, and stormflow simulated for each event (Schmidt and Schulze, 1987a). A frequency analysis was then performed on the simulated flows, thereby accounting for the joint association between rainfall, antecedent soil water and stormflow response. Since a frequency analysis was performed on the simulated flows for a relatively short period of available input data (approximately 20 years at the time the method was developed), the method only provides design flood estimates up to the 20-year return period, and extrapolation beyond the 20-year return period is not recommended (Schmidt and Schulze, 1987a). In addition, the method was only run for a range of *CN-II* values (50, 60, 70, 80 and 90), consequently design stormflow estimates extracted for *CN-II* values within these ranges are interpolated.

Similar to the JAM results, the MCM adjustments are based on the relatively short rainfall records available at the time of the development of the approaches (late 1980s). In addition, the antecedent soil water adjustment procedures for both the MCM and JAM were made based on a simple 3 x 3 x 3 matrix of soil depth classes, vegetation cover classes and soil textural classes for a total of 712 homogeneous climate regions defined at the time for South Africa. This is relatively limited compared to the range of possible soil characteristics and variety of vegetation properties and classes that can be represented in the *ACRU* model today, as well as further sub-division of the country into 1 946 quaternary catchments and 5 838 quinary level sub-catchment regions (Schulze, 2013). South Africa has been divided into primary, secondary and tertiary catchments based on drainage lines and topography. These divisions, however, were found to be too coarse and therefore the tertiary catchments were divided into 1 946 quaternary catchments. The quaternary catchments start at the headwaters of each tertiary catchment and cascade down, following natural drainage lines, to the outlet of each tertiary catchment (Schulze, 2013). Smithers *et al.* (2007) and Smithers *et al.* (2013), however, identified that the model performs better when discretising quaternary catchments into smaller sub-catchments which are more homogeneous in terms of climate, land cover and soils. Based on these findings, each quaternary catchment was further sub-divided into three regions based on natural breaks in altitude, resulting in 5 838 quinary level sub-catchment regions (Schulze and Horan, 2010).

As a result of the above, there is a need to update both the MCM and JAM using the extended records and CSM capabilities currently available. Consequently, additional motivation to further develop and assess a CSM system for DFE in South Africa is evident, since the results and output from the approach may be used to update the SCS-SA model.

In terms of the *ACRU* model, the various components of the hydrological cycle are represented as depicted in Figure 1.2.

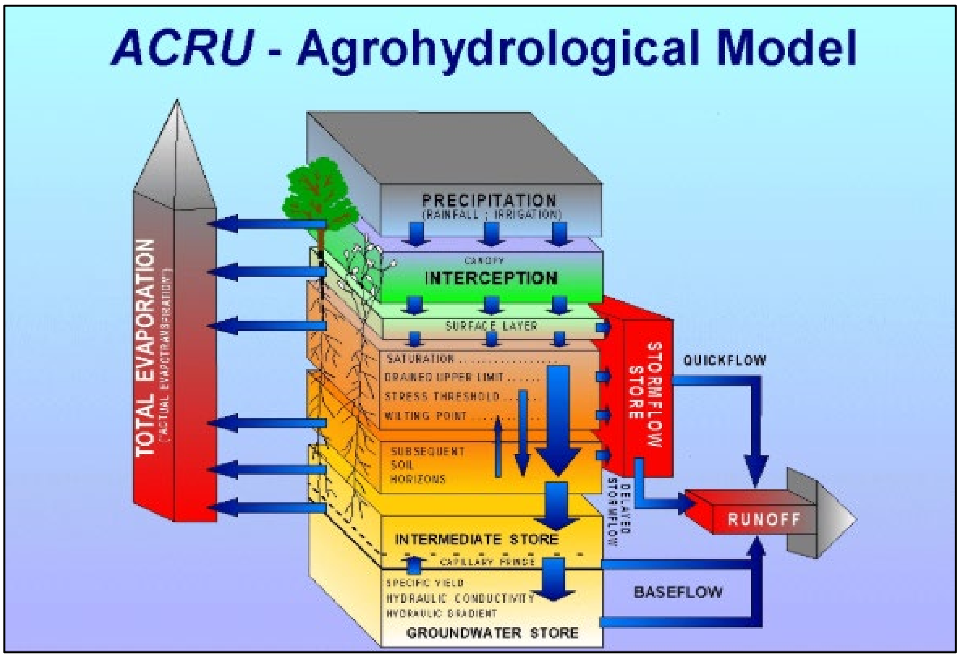

Figure 1.2 Conceptualised hydrological components and processes as structured in the *ACRU* model (Schulze, 1995)

With reference to Figure 1.2 and Equation 1.1, surface and near-surface runoff, i.e. stormflow (*Q*), is simulated daily in the *ACRU* model, using the daily rainfall depth for the day, i.e. from historical rainfall records of observed data input to the model, minus interception which is land cover specific. The c value, referred to as the COIAM in the *ACRU* model, varies from month-to-month and is land cover specific. In contrast to the SCS-SA model, *S* is calculated daily by the multi-layer soil water budgeting techniques of the *ACRU* model. *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. *S* is calculated for a selected Critical Response Depth of the Soil (*SMDDEP*), generally defaulted to the depth of the topsoil horizon, but may be adjusted based 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 stormflow generated is therefore strongly influenced by the *SMDDEP* and the soil water content of the soil prior to a rainfall event. In addition, the daily release of *Q* is controlled by a Quick Flow Response Coefficient (*QFRESP*) which partitions *Q* into a Same Day Response Fraction (*UQFLOW*) and a delayed stormflow response which is added to the next days' stormflow, which is again partitioned based on the *QFRESP* coefficient. *QFRESP* is generally defaulted to a value of 0.3 in the *ACRU* model, based on research undertaken in the Mgeni Catchment (Kienzle and Schulze, 1995).

The residual rainfall, that is not intercepted or converted to stormflow, infiltrates into the topsoil and replenishes the soil water store via the following processes (Smithers and Schulze, 2004):

(i) Once the topsoil reaches field capacity, "excess" water percolates into the subsoil as saturated drainage, *i.e.* the soil structure within the *ACRU* model is divided into a topsoil and subsoil horizon, an intermediate zone and a groundwater store (Figure 1.2).

(ii) The rate of drainage from the topsoil into the subsoil 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 shallow groundwater (baseflow) store which contributes to streamflow as baseflow (Figure 1.2). Baseflow is modelled explicitly in the *ACRU* model.

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

The ability of the *ACRU* model to account for, and explicitly represent, the baseflow contribution to total streamflow, i.e. baseflow and stormflow, is a major benefit compared to the SCS-SA model which simulates stormflow only.

Based on: (i) a lack of observed data on hydrological responses from land cover classes with specific land management practices and hydrological conditions, as defined in the SCS-SA land cover classification, (ii) the similarities between the SCS-SA and *ACRU* models, (iii) the fact that the SCS-SA land cover classification includes classes that are not defined for *ACRU*, and (iv) the widespread use of the SCS-SA model, Rowe (2015) investigated and identified a preliminary approach to represent SCS-SA land cover classes in *ACRU*. This involved assigning a representative *ACRU* land cover class to selected SCS-SA land cover classes and calibrating the *ACRU QFRESP* and *SMDDEP* parameters to SCS-SA *CN*s for each specific land cover, land management practice and hydrological condition class, for the range of hydrological soil groups (A – D) defined in the SCS-SA land cover classification (Schmidt and Schulze, 1987a; Schulze *et al.*, 2004). A methodology and specific rules and equations were developed to achieve this, as detailed by Rowe *et al.* (2018). Further development and assessment of the method and preliminary rules and equations, a full list of which is provided in Rowe (2015), was recommended for the development and assessment of a comprehensive CSM system for DFE in South Africa (Rowe, 2015; Rowe *et al.*, 2018).

Therefore, considering the benefits of the CSM approach to DFE over event-based methods such as the SCS-SA model, and the potential to use the results from the method to update the antecedent soil water adjustment procedures of the widely used SCS-SA model, development and assessment of a comprehensive CSM system applicable to small catchments in South Africa is needed, as motivated for and recommended in the NFSP.

It is important to note that the lack of suitable observed hydrological data in South Africa, as reported later in this document, strongly dictated the research approach applied in this study, as well as that adopted by Rowe (2015) and Rowe *et al.* (2018). In this study, which is a continuation of the study initiated by Rowe (2015) and Rowe *et al.* (2018), the assumption has been made that the hydrological responses simulated by the SCS-SA model, for the range of land cover classes defined in the SCS-SA land cover classification, are reasonable and representative of these land cover classes. The reliance on the SCS-SA model and associated CNs is attributed to the absence of observed data on hydrological responses from a range of land cover classes and soil combinations as defined in the SCS-SA land cover classification in South Africa. Consequently, the results simulated by the SCS-SA model for the range of soils and land cover classes defined in the SCS-SA model have been used as a surrogate for observed data to simulate similar relative magnitudes and changes in stormflow response in *ACRU*. Therefore, the approach to this research has been to improve the conceptual basis of representing land management and hydrological condition classes in the *ACRU* model, based on the responses calibrated into the SCS-SA model through the CN, with verification of the conceptual developments where possible using the limited observed rainfall and runoff data available.

## 1.3 Aim and Objectives of Research

The aim of this research is to further develop and assess the performance of a comprehensive CSM system, that can be used to consistently and reliably estimate design flood discharges in small catchments (0 - 100 km$^2$), throughout South Africa, and which can be easily applied by practitioners. Specific objectives include the following:

(i) Review CSM for DFE from both the international and local literature, in order to identify important findings and trends regarding the development and application of CSM approaches in practice. The focus is on what has been achieved locally in South Africa regarding CSM for DFE and to outline steps, in order of priority, required to develop a comprehensive CSM system for DFE practice in South Africa.

(ii) Development of a comprehensive CSM system including defining a structure and rules on how to implement the system, defining a land cover and soils classification to apply with the system, and assigning default input information to use with the system, i.e. when site-specific information is not available.

(iii) Assess the performance of the above CSM system on selected catchments and, based on the results, perform any refinements or additional investigations to improve on the CSM system.

(iv) Assess the impact of model configuration and application on the performance of the CSM system developed and, based on the results, propose a final CSM system for DFE in South Africa.

(v) Assess and compare the performance of the final CSM system proposed to that of the conventional SCS-SA model and associated antecedent soil water adjustment procedures, i.e. the MCM and JAM. This assessment will indicate and quantify the improvement, if any, in the design flood estimates when applying the CSM system developed as opposed to the traditional SCS-SA approaches.

It is hypothesised that the CSM system developed will provide better results compared to the current default implementation of the *ACRU* model, as well as the traditional SCS-SA approaches. In addition, the CSM system developed will provide a good baseline system from which continued growth and improvement may flourish. Each of the specific objectives listed above are addressed in self-contained chapters within the thesis, as detailed in the following section.

## 1.4 Outline of Thesis Structure

This thesis has been structured into chapters that lead on from one another, as summarised in Table 1.2.

Table 1.2 Outline of thesis chapters

| |
|---|
| **Chapter 1:**<br>Introduction |
| **Chapter 2: Objective (i)**<br>Review of Continuous Simulation Modelling for Design Flood Estimation – A South African Perspective and Recommendations |
| **Chapter 3: Objective (ii)**<br>Development of an Improved Comprehensive Continuous Simulation Modelling System for Design Flood Estimation in South Africa using the *ACRU* Model |
| **Chapter 4: Objective (iii)**<br>Performance Assessment of the Improved Continuous Simulation Modelling System Developed Compared to the Current Default *ACRU* Model |
| **Chapter 5: Objective (iii)**<br>Performance and Sensitivity Analysis of the SCS-Based Peak Discharge Estimation in the *ACRU* Model |
| **Chapter 6: Objective (iv)**<br>Impact of Model Configuration and Parameter Estimation on the Performance of the Continuous Simulation Modelling System Developed and a Proposal for a Final System |
| **Chapter 7: Objective (v)**<br>A Comparative Performance Assessment between the Final Continuous Simulation Modelling System Proposed and the Traditional SCS-SA Model |
| **Chapter 8:**<br>Discussion, Conclusions and Recommendations |

Each chapter addresses one of the specific objectives listed in Section 1.3, in a stepwise manner. The chapters are structured in a paper-like format, with the intent to publish the results from each chapter as individual papers. However, to avoid repetition due to the links between chapters, this document is presented in a traditional thesis format. Consequently, reference is made to previous chapters where needed, to avoid repetition of information. Each chapter contains an introduction, methodology, results and discussion, conclusions and recommendations section.

# 2. REVIEW OF CONTINUOUS SIMULATION MODELLING FOR DESIGN FLOOD ESTIMATION – A SOUTH AFRICAN PERSPECTIVE AND RECOMMENDATIONS

This chapter is based on the following paper:

Rowe, TJ* and Smithers, JC. 2018. Review: Continuous simulation modelling for design flood estimation – a South African perspective and recommendations. *Water SA 44* (4): 691-705. DOI: 10.4314/wsa.v44i4.18.

## 2.1 Abstract

A number of severe flooding events have occurred both in South Africa and internationally over recent years. Furthermore, changes in both the intensity and frequency of extreme rainfall events has been documented, both locally and internationally, associated with climate change. The recent loss of life, destruction of infrastructure, and associated economic losses caused by flooding, compounded by the probability of increased rainfall variability in the future, highlight that Design Flood Estimation (DFE) techniques within South Africa are outdated and are in need of revision. A National Flood Studies Programme (NFSP) has recently been initiated to overhaul DFE procedures in South Africa. One of the recommendations in the NFSP is the further development of a Continuous Simulation Modelling (CSM) system for DFE in South Africa. The focus of this chapter is a review of CSM techniques for DFE, to guide further development for application in South Africa. An introduction to DFE, and particularly the CSM approach, is firstly presented followed by a brief overview of DFE techniques used in South Africa, leading into a more detailed summary of CSM for DFE within South Africa to date. This is followed by a review of the development and application of CSM methods for DFE internationally, with a focus on the United Kingdom and Australia, where methods have been developed with the intention of national scale implementation. It is important to highlight that there are a plethora of CSM methods available internationally and this review is not exhaustive and focusses on and identifies some of the strengths and weaknesses of several popular methods, particularly those intended for national scale application, as the intended outcome from this review is to identify a path towards the development of a usable national scale CSM system for DFE in South Africa. Emphasis on a usable method is important, considering the

reality that, despite promising results, numerous benefits, and national scale methods being developed, it appears that the CSM method for DFE is rarely used in practice.

***Keywords:*** *Design flood estimation, continuous simulation, South Africa, SCS-SA and ACRU models, United Kingdom, Australia*

## 2.2 Introduction

The assessment of flood risk by associating a flood event with a probability of exceedance or return period is the standard approach to Design Flood Estimation (DFE) in most countries (Smithers, 2012; Kang *et al.*, 2013). This is essential to the planning, prevention and control of the damaging effects of flooding to hydraulic infrastructure such as dams, bridges and culverts, and to development sites situated within the floodplain (Lamb *et al.*, 2016).

DFE techniques for most countries can be categorised into two broad groups, which generally include: (i) approaches based on the statistical analysis of observed peak discharges, and (ii) rainfall-runoff simulation based on either event modelling or Continuous Simulation Modelling (CSM) (Smithers, 2012). The approaches to DFE in South Africa are outdated and are in need of revision (Alexander, 2002; Görgens, 2007; Smithers, 2012; van Vuuren *et al.*, 2013). Consequently a National Flood Studies Programme (NFSP), aimed at updating and modernising the various approaches to DFE used in South Africa, has recently been proposed and initiated (Smithers *et al.*, 2016).

Alexander (2002) highlighted the need to update DFE procedures, after severe flooding in southern Africa in 1999 and 2000, and this was supported by Smithers (2012) after flooding in the Western Cape in 2005 and in the Free State and Eastern Cape in 2011. A recent review of flooding events reported in FloodList (2016) highlighted several large flood events across the globe in 2016 including, *inter alia*, Germany, Romania, China, Paris – France, the Ukraine, the United States, Belgium and Russia. Several of these floods at specific locations exceeded previous records (FloodList, 2016). Furthermore, a recent report by the United Nations (UN) states that over the past 20 years (1995 – 2015), approximately 157 000 people have died as a result of flooding, with a further 2.3 billion people affected by the damaging effects of flooding over the same period (UNISDR, 2015). According to the United Nations Office for Disaster

Risk Reduction (UNISDR, 2015), flooding accounts for approximately 56 % of weather related disasters, with the remaining 44 % accounted for as follows: drought ≈ 26 %, storms ≈ 16 %, extreme temperatures, landslides and wildfire ≈ 2 %. South Africa has also experienced recent flooding with floods reported in and around Durban (July, 2016), with record breaking rainfall depths, five deaths, and damages totalling millions of Rands (FloodList, 2016). During the same period the Western Cape experienced floods that affected more than 10 000 people, as reported by local disaster management officials (FloodList, 2016).

The recent flooding emphasises the need to update DFE methods in South Africa, further motivated by evidence and projections of possible changes in both the intensity, frequency and seasonality of extreme rainfall events in South Africa, i.e. as a result of human-induced climate change (Ndiritu, 2005; Kruger, 2006; Du Plessis and Burger, 2015; Kruger and Nxumalo, 2017). Hrachowitz *et al.* (2013) and Kusangaya *et al.* (2014) also allude to such phenomena, where alterations in rainfall patterns, and an increased prevalence and intensity of natural hazards has been observed. This adds an additional dynamic to DFE that needs to be accounted for and the CSM approach has significant potential to accommodate such scenarios, i.e. changing input data and model parameters to simulate future flood characteristics. These include, for example, changes in rainfall patterns, local climate, land cover and catchment physiographical changes (Lamb *et al.*, 2016; Vogel, 2017). This is a significant advantage of the CSM approach to DFE over approaches based only on the analysis of observed runoff, with the inherent assumption of stationarity and the extrapolation of higher return period floods based on the limited number of observed records available (COST, 2013).

The origins of CSM date back to the late 1950s with the Stanford Watershed Model, the first computer based continuous hydrologic simulation model developed (Crawford and Burges, 2004). The method evolved over the period from 1959 to 1974, and led to the development of the computer code known as the Hydrologic Simulation Program Fortran (HSPF), produced for and with the support of the United States Environmental Protection Agency – USEPA (Crawford and Burges, 2004). Since then continual development, motivation for, and experimentation with, the CSM approach to runoff simulation has been documented within the literature, as reviewed in this paper, and has resulted in the plethora of currently available Continuous Simulation (CS) rainfall-runoff models. The benefits of the CSM approach to DFE over traditional event-based rainfall-runoff techniques include the ability of the method to account for: (i) constant and changing catchment characteristics (e.g. land cover and climate), (ii) the impact of antecedent soil water conditions on runoff generation, and (iii) a more comprehensive representation of hydrological processes. Lamb *et al.* (2016) provides additional examples of the benefits of a CSM approach and case studies where the CSM approach has been applied in practice to problems too complicated to be adequately assessed with the event-based or statistical methods available in the United Kingdom, further details of which are provided later in this chapter.

The CSM approach, like many of the rainfall-runoff methods used in South Africa, is generally applicable to small catchments (< 50 km$^2$). According to Smithers *et al.* (2016), the majority of the catchments (55 %) for which design floods are required in South Africa are relatively small (< 15 km$^2$). Therefore, based on the advantages of the CSM approach as alluded to above, and as reviewed in detail throughout this chapter, the benefit of developing a CSM methodology for DFE in small catchments, applicable at a national scale in South Africa, is highlighted. In addition, comparison of this method to alternative event-based, empirical and statistical methods may then be performed.

In this chapter, the use of CSM for DFE is critically reviewed, both within South Africa and internationally. The objective of the review is to: (i) outline the general framework and options available when implementing a CSM approach for DFE, (ii) summarise the developments towards a CSM approach to DFE in South Africa, and (iii) identify approaches from the international literature which could be used in the further development of a CSM approach for South Africa. The international review is focussed on two countries, namely the United Kingdom and Australia. These countries are at the forefront in terms of flood studies research internationally, with both countries recently revising the techniques and methodologies applied to estimate design floods at a national scale. The literature review is followed by a discussion of the review relevant to further development of a CSM system for DFE in South Africa.

## 2.3 Generalised Framework for Continuous Simulation Modelling

This section will briefly describe the general framework towards implementation of a CSM approach to DFE, including the various steps, options and associated models that may be incorporated into the approach. In general, a CSM approach requires time-series inputs of climate data such as rainfall and evapotranspiration. At a bare minimum, however, rainfall data is essential for all CS models, and the quality of the data is of upmost importance as the rainfall is the main driver of runoff production. Depending on the CS model selected, these inputs may be required at various time-steps from daily, hourly, to sub-hourly. In general the finer the resolution of the time-step the more sparse the availability of data. In terms of rainfall data, daily rainfall values are more readily available and are of longer record length (Smithers and Schulze, 2000; Grimaldi *et al.*, 2012).

In the simplest case, observed rainfall records, of suitable length, if available may be used directly as input to a CS model to obtain an output of simulated flow time-series. In many cases, however, long records of rainfall within a region may not be available or the records are relatively short. This is a particularly large problem when estimating design floods, where long records are needed to obtain more reliable and accurate estimates of flood quantiles at the higher return periods.

For this reason stochastic rainfall generators are commonly used with CS models, as well as many other rainfall-runoff simulation based approaches, to generate or extended rainfall records (e.g. Beven, 1987; Smithers *et al.*, 2000; Clothier and Pegram, 2002; Frezghi, 2005; Sivapalan *et al.*, 2005; Rogger *et al.*, 2012; Sharma *et al.*, 2016; Arnaud *et al.*, 2017; Odry and Arnaud, 2017). Similarly, rainfall disaggregation models, or simple disaggregation techniques, are also commonly applied to generate short duration data from longer time-steps, e.g. daily to hourly (Calver *et al.*, 2005; Knoesen, 2005; Knoesen and Smithers, 2009; Grimaldi *et al.*, 2012; Haberlandt and Radtke, 2014; Nathan and Ling, 2016). Therefore, a plethora of rainfall generation as well as disaggregation models have been developed and implemented with CSM approaches internationally, with limited experimentation in South Africa as reviewed in the next section. An exhaustive review on these methods is not provided in this chapter, since the focus is on the CS rainfall-runoff models themselves, based on the following reasoning. It is believed that developing a robust CS model that can be validated using actual observed rainfall and runoff data is a critical first step and, once validated, further system development such as rainfall generators or disaggregation techniques should be considered, since they provide significant benefit in terms of extending rainfall record lengths and plausible sequences of events not evident in the observed record. Furthermore, it should be noted that an additional source of uncertainty is introduced when incorporating these stochastic and disaggregation rainfall models. The significant value and potential of these techniques, however, is acknowledged, and further implementation and development of these approaches is recommended, and should likely be included in all simulation based approaches in South Africa in the future. This may become more critical if the trend of diminishing hydrological data networks, as identified by Wessels and Rooseboom (2009) and Pitman (2011), and which is persisting in South Africa continues. It should be noted, however, that a national database with 50 years of rainfall, temperature, Apan evaporation and other climate variables is available in South Africa, and has been used extensively with the *ACRU* model for various water resources management applications (Smithers and Schulze, 2004), including DFE as reviewed in the following section. Ideally, the availability of a database of observed rainfall, estimated evaporation and observed runoff is required for CS model development and verification as this enables the CS model to be used with confidence in stochastic simulations. Thereafter the use of stochastic rainfall models provide additional benefits, including: (i) extending the length of rainfall records and uncertainty estimation with an ensemble or Monte-Carlo type approach (Weinmann *et al.*, 2002; Nathan and Weinmann, 2013; Nathan and Ball, 2016; Nathan and Ling, 2016), i.e. generating thousands of rainfall time-series to simulate thousands of runoff time series to obtain a range of possible simulations, and (ii) accounting for the effects of climate change by incorporating these scenarios into the models (Lamb *et al.*, 2016; Vogel, 2017).

Another important component of both stochastic rainfall models and CS rainfall-runoff models is parameter calibration. In most cases model parameters are calibrated against observed data, i.e. parameters are optimised until the best fit between the simulated and observed data is obtained, which is assessed using an objective function such as the Root Mean Squared Error (RMSE) or the Nash-Sutcliffe Efficiency (NSE) (Blöschl *et al.*, 2013). A regionalisation approach is required to estimate the model parameters at ungauged locations. Several regionalisation techniques are available such as spatial proximity and similarity pooling, a region-of-influence type approach, regression-based methods or cluster analysis (Smithers, 2012; Blöschl *et al.*, 2013; COST, 2013; Odry and Arnaud, 2017). In the case of the *ACRU* model in South Africa direct calibration of model parameters is not performed (Schulze, 1995). Model parameters are linked to physical catchment characteristics, and observed data is only used to verify the model simulations. Consequently, the need for direct regionalisation of parameters is not necessary, although parameters may be derived from catchment characteristics which do vary regionally, therefore regionalisation approaches are not a focus of this chapter. The advantage of the physical-conceptual nature of the *ACRU* model, with parameter values generally linked to catchment characteristics, is that the structure of the model and process representations are based on an increased knowledge and understanding of hydrological processes and their interactions at various scales (Schulze, 1995). Hrachowitz *et al.* (2013) believe that this is essential to improve predictions in ungauged basins, and Lamb *et al.* (2016) highlights this as one of the greatest advantages of the CSM approach.

When using a CSM approach for DFE, a standard Flood Frequency Analysis (FFA) is performed by fitting a suitable probability distribution to the Annual Maximum Series (AMS) or a Peak Over Thresholds (POT) series extracted from the simulated flows (Ball, 2013; Ling *et al.*, 2015). Alternatively, a direct frequency analysis on all flows may be performed (Lamb *et al.*, 2016). The FFA can be performed to estimate both flood volume and peak discharge quantiles. In most cases these estimates are required as input to a hydraulic model, or a flood routing model, for floodplain delineation or the design and management of hydraulic structures and systems (Lamb *et al.*, 2016). Hydraulic modelling is then performed to determine the inundation levels of the flood based on flood peak, volume and full flood hydrographs (Lamb *et al.*, 2016). The advantage of a CSM approach is that a coherent set of all three components is simulated by the model (Lamb *et al.*, 2016). Odry and Arnaud (2017) highlight that statistical FFA methods often estimate flood volumes and peak discharges independently, and therefore the joint association between peaks and volumes is not maintained. In addition other event-based methods such as the Rational Method only estimate peak discharges (Smithers, 2012). In summary, hydrological outputs from any FFA method are often used as direct inputs to hydraulic models such as HEC-RAS as used, for example, extensively by the South African National Roads Agency Limited (SANRAL, 2013). Hydraulic modelling of floods are not reviewed in great detail in this chapter since the focus is on the CS models applied. Ultimately the choice of DFE method selected is dependent on the type of problem or project under investigation, as well as practical constraints such as budget and time.

## 2.4 Design Flood Estimation in South Africa

A number of approaches to design flood estimation have been developed for application in South Africa. This section provides a brief overview of the approaches and then focusses on the use of continuous simulation modelling.

### 2.4.1 Overview of approaches

Smithers (2012) and Smithers *et al.* (2013) categorise DFE techniques used in South Africa into two groups: (i) the analysis of observed flow data, and (ii) rainfall-runoff based methods, as shown in Figure 2.1.

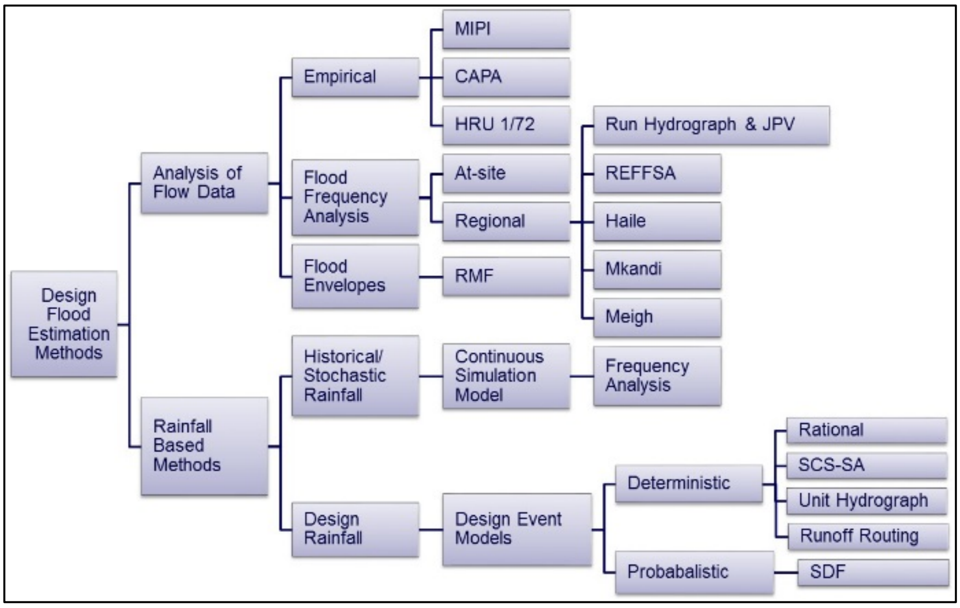

Figure 2.1 Design flood estimation methodologies within South Africa (after Smithers, 2012)

Detailed reviews of the various methods for DFE in South Africa are provided in, *inter alia*, Smithers (2012), SANRAL (2013) and Rowe (2015). Many of the methods, however, are outdated and consequently a NFSP, aimed at modernising and updating the various approaches to DFE within South Africa, has been initiated (Smithers *et al.*, 2016). The focus of this study is on the rainfall-runoff CSM approach, one of the methods recommended for development in the NFSP. Consequently, the next section contains a review of the developments towards a CSM approach for DFE in South Africa.

### 2.4.2 Continuous simulation modelling and associated developments

In South Africa reasonable results have been obtained from the successful application of the CSM approach for DFE in a number of pilot studies (Smithers *et al.*, 1997; Smithers *et al.*, 2001; Chetty and Smithers, 2005; Smithers *et al.*, 2007; Smithers *et al.*, 2013). The CS model used in all these studies was the physically-based, conceptual, daily time-step *ACRU* agrohydrological model (Schulze, 1995). The model, developed at the University of KwaZulu-Natal (formerly the University of Natal) in South Africa, has been extensively verified and accepted for a range of practical water resources management applications, including experimentation as a tool for DFE in several pilot studies, as alluded to above (Schmidt and Schulze, 1987a; Schulze *et al.*, 2004; SANRAL, 2013). A brief description and summary of the investigations performed in some of these pilot studies is presented below. However, for further details of the investigations and results refer to Smithers *et al.* (2001); Smithers *et al.* (2007); Smithers *et al.* (2013) and Rowe (2015).

Smithers *et al.* (2001) performed a range of assessments on the extreme rainfall and flooding experienced over the north-eastern parts of South Africa, Mozambique and Zimbabwe during the February 2000 floods caused by tropical depressions and cyclone activity, using the Sabie River catchment upstream of the South Africa / Mozambique border as a case study (6260 km$^2$). The *ACRU* CS model was used to validate the peak discharge estimates derived from surveyed flood lines and hydraulic calculations (Van Bladeren and Van der Spuy, 2000), i.e. since the exceptional flooding resulted in the failure and destruction of several gauging stations (Van Biljon, 2000) and therefore no observed flow data were available at many gauging stations. Furthermore, the primary streamflow data for many of the gauges in the catchment were found to be unreliable due to flows regularly exceeding the rating capabilities of these structures, and consequently the *ACRU* model was used to simulate streamflow and peak discharges over these periods (Smithers *et al.*, 2001). The importance of using a CSM approach in this case lies in the ability of the method to explicitly represent antecedent soil water conditions during the build-up to the events that produced the highest peaks, where it was highlighted that antecedent conditions played an important role in the severity of the events. In addition, the ability to model the catchment in distributed mode and consequently account for the non-uniformity of rainfall was necessary, i.e. since the rainfall and hence flooding, was considerably spatially variable within the catchment. The modelling in distributed mode also required flood routing, all of which the CSM approach could provide (Smithers *et al.*, 2001). The *ACRU* simulations for the February 2000 events were in close agreement with the hydraulically derived estimates of Van Bladeren and Van der Spuy (2000), i.e. where observed estimates were not available. Comparison of the observed and simulated Flood Frequency Curves (FFCs) for gauges that had adequate observed data highlighted that the simulated results closely mimicked the observed data, particularly for the higher return period events. In addition the spatial variability of the rainfall and flooding, in terms of magnitude and their associated return period at different points in the catchment, for the February 2000 events could be adequately represented and mapped using the *ACRU* simulated results (Smithers *et al.*, 2001).

Smithers *et al.* (2007) and a summary paper by Smithers *et al.* (2013), present the results of several research projects that have contributed to the development and application of the *ACRU* modelling system for DFE. These refinements and developments to the *ACRU* modelling system were incorporated into the *ACRU* model by Smithers *et al.* (2007) and the methodology assessed using the Thukela Catchment (29 036 km$^2$) in South Africa as a case study.

The results highlighted the difficulty associated with applying the model to an operational catchment, i.e. where land cover changes and water abstractions occur and are not documented. Verification was further complicated by errors in observed data, sparse raingauge networks and problems with rating tables (Smithers *et al.*, 2013). In summary, the results indicate that disaggregating catchments into smaller homogeneous subcatchments or Hydrological Response Units (HRUs) is required and that area weighted soils and land cover information, rather than lumped information, produced more realistic results. The benefit of using a representative driver rainfall station for each subcatchment, as opposed to a single driver rainfall station for the whole catchment, was also evident. The importance of extended historical rainfall records and accurate land cover information was also identified.

Frezghi (2005) 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. 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). At this point, it is important to mention that additional experimentation with different stochastic rainfall models in South Africa has been performed (e.g. Zucchini *et al.*, 1992; Smithers and Schulze, 2000; Smithers *et al.*, 2000; Smithers *et al.*, 2002). Smithers and Schulze (2000) for example assessed the performance of two variations of the Bartlett-Lewis rectangular pulse type of intra-daily stochastic models to estimate short duration design rainfall in South Africa, and found the methods performed reasonably well when calibrated to both short duration data and daily data.

In addition to the stochastic model assessed by Frezghi (2005), 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). The model performed reasonably well with some suggestions to further refine certain aspects of the model (Smithers *et al.*, 2013).

Further research on the temporal distribution of rainfall, methods to stochastically generate rainfall over a catchment, improvement to the estimation of catchment response times, and further development of flood routing methods for application in ungauged river reaches was also suggested. Ultimately, however, the results of Smithers *et al.* (2007), and summary of the results by Smithers *et al.* (2013), highlight the potential of the *ACRU* CS model to reproduce reliable and consistent estimates of design floods. Although promising results have been obtained, no CSM methodology has been developed to be applicable at a national scale, such as is available for the event-based SCS-SA model. Consequently, Rowe (2015) initiated preliminary investigations towards the development of a national scale CSM methodology for DFE within South Africa using the *ACRU* model.

Rowe (2015) highlighted that the *ACRU* model uses the same SCS (1956) runoff equation as the SCS-SA event-based model (Schmidt and Schulze, 1987a) to estimate stormflow, there are however significant differences in model structure and how the parameters of the runoff equation are estimated, particularly the potential maximum soil water retention, or the soil water deficit (*S*). In the SCS-SA model *S* is estimated using a single parameter, the catchment Curve Number (*CN*), which accounts for soil properties, land cover, land management, hydrological condition and antecedent soil water content. Initial *CN*s may be adjusted to account for the antecedent soil water conditions. The median condition and joint association methods (Schmidt and Schulze, 1987a), which used the *ACRU* soil water budgeting routines to estimate the antecedent conditions for a 30 day period prior to large rainfall events, were a major improvement to the original water adjustment procedure introduced into the original SCS (1956) model. Therefore, the *ACRU* CSM approach has significant potential in improving the estimation of losses in event-based methods such as the SCS-SA model. Consequently, further development of the *ACRU* CSM approach provides the opportunity to update and possibly revise the SCS-SA soil water adjustment techniques.

Rowe (2015) also noted that there is value in the *CN* in terms of accounting for the strong effects of soil and land cover properties on stormflow generation. In addition it was identified that the SCS-SA land cover classification accounts for different land management practices and hydrological conditions, which are not explicitly accounted for in the current *ACRU* land cover classifications. Consequently, Rowe (2015) undertook a study to determine how to represent land cover classes, as represented within the SCS-SA classification (Schulze *et al.*, 2004), within the *ACRU* model. This was achieved by using the design stormflow volumes simulated by the SCS-SA model as a surrogate for observed data. The differences in design stormflow volumes simulated by the SCS-SA model were used as a reference to simulate similar design stormflow volumes and changes in design stormflow volumes with the *ACRU* model, applying the following steps:

(i) Attempts were initially made to achieve equivalence of soil representations between the SCS-SA and *ACRU* models, i.e. how to represent SCS-SA soil groups A – D in *ACRU*. Three attempts were made using soil textural properties to represent SCS-SA soil groups, however, it was found that SCS-SA soil groups could not be represented in the *ACRU* model by soil textural properties alone.

(ii) Consequently, a sensitivity analysis of several *ACRU* parameters was conducted in order to identify which *ACRU* parameters to use to represent SCS-SA soils and *CN*s best, for selected land cover classes.

(iii) Two *ACRU* parameters namely, *QFRESP*, a Quick Flow Response Coefficient which partitions stormflow into a same day response fraction and a subsequent delayed stormflow response, and *SMDDEP*, which determines the critical hydrological response depth of the soil, were identified as sensitive parameters suitable to represent SCS-SA soils and land cover classes.

(iv) Through manual calibration *QFRESP* and *SMDDEP* values corresponding to a SCS-SA soil group and land cover class were identified to represent that land cover class in *ACRU*, i.e. by adjusting the *QFRESP* and *SMDDEP* parameters in the *ACRU* model until similar stormflow volumes to those simulated by the SCS-SA model were obtained for a similar land cover in *ACRU.*

A strong relationship between these *ACRU* parameters and *CN* values for selected SCS-SA soil groups and land cover classes was found and consequently preliminarily rules and equations were developed to represent SCS-SA land cover classes in *ACRU* (Table 8.1: Rowe, 2015).

The following recommendations were made to further validate and verify the approach and to further the development of a CSM system for DFE in South Africa (Rowe, 2015):

(i) The rules and equations derived from the experimentation with three land cover classes (veld/grassland, row crop/maize, small grain/wheat) were tested on a single land cover class, sugarcane. Therefore, only four land cover classes within the SCS-SA classification, out of a total of nine, were investigated. Consequently, the rules and equations derived in the study were identified as preliminary best estimates, with further investigation and validation of the approach being required including:

- the analysis of additional land cover classes,
- further independent verification at different geographical locations, and
- verification of the simulated results against observed data, in terms of both streamflow volumes and peak discharges.

(ii) Land cover information, based on the Acocks (1988) natural land cover map, needs to be updated with current actual land cover information.

(iii) The development of a CSM system or methodology is needed, i.e. how the system will be compiled or packaged for use at a national scale within South Africa.

Verification of the simulated results in terms of peak discharges, i.e. in addition to streamflow volumes, is important as flood peaks are typically required for the design of hydraulic infrastructure. Due to the large variability in the streamflow response of catchments to storm rainfall, peak discharge estimation, particularly in ungauged catchments, continues to be a challenge in the field of hydrology both within South Africa and internationally (Gericke and Smithers, 2014). Catchment response time parameters, which impact directly on the hydrograph shape and peak discharge, are generally required as a primary input to most rainfall-runoff methods, including the CSM approach. The most frequently used catchment response time parameters are the Time of Concentration ($T_C$), Time Lag ($T_L$) and Time to Peak ($T_P$) (Gericke and Smithers, 2014).

From a review of methods used both locally in South Africa and internationally to estimate catchment response time parameters, Gericke and Smithers (2014) identified inconsistencies between the methods, i.e. when compared to the recommended methods for South Africa, which were also shown to be used outside of the boundaries (location and catchment area) used to develop the methods. Identifying the need for an alternative, improved and consistent approach to estimate catchment response time, Gericke and Smithers (2016); Gericke and Smithers (2017); and Gericke and Smithers (2018) developed regionalised empirical equations to estimate catchment response times, expressed as the time to peak discharge ($T_P$). The new empirically derived time parameter equations were tested on four climatologically different regions within South Africa and the results indicate that the method provides improved peak discharge estimates at ungauged catchments within these specific regions. Further development of the method to extend applicability to a national scale is recommended (Gericke and Smithers, 2016; Gericke and Smithers, 2018). Gericke and Smithers (2016) recommended that the improved methodology be included in both event-based and CSM DFE methods in South Africa in order to obtain improved peak discharge estimates. Therefore, the inclusion of the new methodology for estimating catchment response time needs to be incorporated in the development of a CSM approach to DFE in South Africa.

The above brief review indicates that some progress has been made towards a CSM approach for DFE in South Africa. However, it is evident that there is still much work to be done to develop a comprehensive CSM methodology for DFE applicable at a national scale. The following sections review CSM developments from the international literature.

## 2.5 Design Flood Estimation in the United Kingdom

The Flood Studies Report (FSR) published by the Natural Environment Research Council (NERC, 1975) is the original guideline for flood estimation within the United Kingdom. This guideline was succeeded by the Flood Estimation Handbook (FEH) published by the IOH

(1999). The FEH and its subsequent updates are extensively utilised to estimate design floods within the United Kingdom. Several statistical methods are available based on the analysis of observed streamflow data, using both at-site and regional approaches (Kjeldsen, 2015). In addition to the statistical approaches to DFE, an event-based FSR rainfall-runoff method (NERC, 1975) and subsequent updates, termed the FSR/FEH rainfall-runoff method is included in the FEH, and is widely applied to generate hydrographs and peak flows (Kjeldsen, 2007; WHS, 2016). The FSR/FEH Revitalized Flood Hydrograph model – ReFH (and updated ReFH2) rainfall-runoff model is made-up of: (i) a loss model, based on the uniform Probability Distributed Model (PDM) of Moore (1985) which is used extensively in the United Kingdom for a variety of hydrological applications, (ii) a routing model, using the commonly applied Unit Hydrograph (UH) concept, and (iii) a baseflow model, based on a linear reservoir concept (Kjeldsen, 2007). In addition to the widely-used event-based approach, several case studies report on the application of CSM approaches to DFE, as reviewed next, followed by a review of a national CSM method for application in the United Kingdom.

### 2.5.1 Continuous simulation modelling – case studies

Calver and Lamb (1995), Calver (1996), Calver *et al.* (1999), Cameron *et al.* (1999), Lamb (1999), Calver *et al.* (2004) and Calver *et al.* (2005), amongst others, have expended considerable effort towards the development of a CSM approach for flood frequency estimation in the United Kingdom.

The research of Calver and Lamb (1995), up to and including the development of a national CSM approach by Calver *et al.* (2005), has focused on national scale assessments and consequently simple parameter-sparse models have been selected, i.e. since parameters need to be derived indirectly from easily obtainable catchment descriptors. Calver *et al.* (2004), however, emphasise that more detailed parameter-intensive CSM models are available for catchment-specific investigations. Such examples include the following models: (i) the Topography-Based Model of Catchment Hydrology (TOPMODEL) to simulate continuous flow series within the Generalised Likelihood Uncertainty Estimation (GLUE) framework, as implemented by Cameron *et al.* (1999), Cameron *et al.* (2000) and Cameron (2006), (ii) the *Systeme Hydrologique European* (SHE) model (Boughton and Droop, 2003; Devi *et al.*, 2015), and (iii) the Hydrological Simulation Model (HYSIM) used widely in the UK water industry including the Environment Agency, as well as application in several other countries (WRA, 2018). A modified version of TOPMODEL within the GLUE framework has also been implemented in the Czech Republic by, inter alia, Blazkova and Beven (2004) and Blazkova and Beven (2009). Although such models are a significant development towards representing and understanding the various components of catchment hydrology, they are generally too complex and parameter-intensive for national scale application and are consequently restricted to application in small research catchments (Boughton and Droop, 2003). Calver and Lamb (1995) identified two suitable simpler models, namely the five-parameter PDM (Moore, 1985) and the three-parameter Time-Area Topographic Extension (TATE) model (Calver, 1996), as applicable models to simulate continuous flow series, from which FFCs may be derived.

Calver and Lamb (1995) assessed the performance of these two simpler models on ten catchments in the United Kingdom, ranging in size from 1 km$^2$ to over 400 km$^2$ with a range of geographical and topographical characteristics. Flood frequencies for both the observed and simulated flows, derived using a partial duration series approach, were also compared and discussed. The results fell within an acceptable range, however, some areas where improvements were needed were identified. It was noted by Calver and Lamb (1995) that data errors, even in a single hourly value of nominally quality-checked data, can exert undue influence on the results.

With regards to data, both Calver and Lamb (1995) and Calver *et al.* (2004), acknowledge that obtaining large data samples of suitable accuracy and record length, especially at sub-daily time scales, is challenging even in a relatively data-rich country such as Britain. This highlights the importance of observed rainfall and streamflow records and is an observation worth noting with regards to the South African context where, as already mentioned, the number of observed rainfall and flow gauging stations are on the decline (Wessels and Rooseboom, 2009; Pitman, 2011).

Following the investigation of Calver and Lamb (1995), Calver *et al.* (1999) continued to experiment with the CSM approach to DFE and produced a “pilot” flood frequency system for Britain using 35 catchments. The research around the CSM approach to DFE culminated in the development of a national CSM river catchment flood frequency method for the United Kingdom (Calver *et al.*, 2005), as reviewed in the next section.

### 2.5.2 Continuous simulation modelling – national approach

Calver *et al.* (2005) report on the development of a national river catchment flood frequency method using CS, where 119 data-rich catchments were used to extend the method developed by Calver and Lamb (1995), Calver *et al.* (1999) and Calver *et al.* (2001), to include full spatial coverage across Britain. The two models selected remained the TATE and PDM models, which had a proven track record of suitable performance.

At the onset, Calver *et al.* (2004) and Calver *et al.* (2005) highlight the advantage of working with data records of smaller time steps, to preserve the definition of flood peaks, where even a simple uniform disaggregation of daily rainfall into hourly totals provided superior results compared to direct use of the daily data. In addition, the benefit of extended records is also emphasised, i.e. to extend the estimation of floods to higher return periods. In terms of model calibration, a two-pass sequential method of automatic calibration was adopted. Quantitatively, for all 119 sites investigated, the mean absolute percentage errors between simulated and observed FFCs, for return periods from 1 to 20 years, ranged from 5 – 11 % for the TATE model, and 4 – 9 % for the PDM model. Calver *et al.* (2005) noted that there was no obvious advantage of one model over the other. Furthermore, there was no obvious dependence of calibration performance on catchment properties, however, relationships between calibrated parameter values and catchment properties were identified. This demonstrated the potential for spatial generalisation of parameter values, required to estimate flood frequencies for all catchments in Great Britain, which include a large proportion of ungauged catchments.

Calver *et al.* (2005) investigated and compared three different spatial generalisation techniques and noted that for each model the best-performing method provided mean percentage errors two to three times greater than those obtained from the calibration procedure. Calver *et al.* (2005) accounted for two sources of uncertainty related to: (i) the spatial generalisation procedure, and (ii) the calibration procedure. The uncertainty measures were used by Calver *et al.* (2005) to determine uncertainty bounds around each of the generalised FFCs for each catchment, *i.e.* treating them as ungauged. The uncertainty bounds were calculated for the 90, 95 and 99 % confidence intervals to better illustrate the asymmetry and spread of the bounds. Quantitatively, the average 50-year return period range of possible flood peak values, at the 99 % confidence interval, ranged from between 1.75 to 2.17 times greater than the generalised estimate for both models at the upper bound and between 2.26 to 3.27 times greater for the lower bound. Therefore, there is considerable uncertainty around the generalised flood peak estimates. Calver *et al.* (2005) also noted that the uncertainties associated with data and model structure, which were not investigated in the study, may also be estimated, and are additional sources of uncertainty to consider.

### 2.5.3 National CSM system versus FEH methods and recommendations

Calver *et al.* (2005) compared the performance of the CSM approach to the FEH event-based methods, i.e. the ReFH rainfall-runoff model and the statistical method, i.e. using at-site data or a regional approach. The comparison is purely qualitative and included some of the following (Calver *et al.*, 2005):

(i) The FEH and former FSR methods are generally preferentially applied compared to the CSM approach, because they a relatively more easy to apply, are well established and well defined, and practitioners are familiar with the approaches and understand how to use them. Furthermore, the methods are less data intensive.

(ii) Therefore, the aim of the study was to develop a comprehensive method and the required software, i.e. including data requirements, within a user-friendly interface, to allow users to obtain results promptly while still providing results with high accuracy. The intent being to facilitate and promote adoption of the CSM approach in practice.

(iii) The CSM approach is superior due to the continuous accounting of antecedent soil water, and the consequent joint probability analysis between rainfall and antecedent conditions.

(iv) The CSM approach is applicable to a larger range of catchment sizes, provided a distributed model setup is implemented.

(v) Furthermore, with respect to return period, it was highlighted that the CSM approach is generally restricted to estimates of lower return periods due to data availability, however, it is noted that this may be extended using stochastic data generation techniques.

(vi) Lastly, in terms of stationarity, the FEH methods assume a stationary climate and catchment conditions. The CSM approach, although calibrated against observed data with the assumption of stationarity, can simulate changes in climate or catchment conditions through the alteration of model parameters and inputs.

In general, recommendations included further testing and validation of the approach and methods developed. Possible variations to the methods need to be developed based on assessment and feedback from testing of the approach. In addition, quantitative comparison of the approach to the FEH methods is emphasised. Packaging of the approach into software and dissemination and adoption of the approach in practice is necessary. Detailed research on stochastically generated time series is recommended, with strong emphasis on uncertainty estimates and the accuracy of the methods tested or investigated. In summary, Calver *et al.* (2004) and Calver *et al.* (2005) suggest that considerable effort is still needed to establish a national CSM method for Flood Frequency Analysis (FFA) at ungauged catchments in the United Kingdom. The potential of the approach, however, is emphasised and Calver *et al.* (2004) noted that addressing these challenges and improving the CSM approach is at the forefront of modelling research.

Since the publication of the national CS flood frequency method for the United Kingdom by Calver *et al.* (2005), limited research related to the CSM approach has been identified within the literature, aside from a subsequent paper by Calver *et al.* (2009). The paper of Calver *et al.* (2009) covers the recommendations of Calver *et al.* (2005) to quantitatively compare the CSM approach to the event-based FEH procedures. 107 catchments in Great Britain, ranging from 10 – 1200 km$^2$, were considered in the study. In general, the CSM approach (Calver *et al.*, 2005) outperformed the FEH event-based procedures. For example, the 50-year return period mean and standard deviation of the absolute percentage error between observed and simulated flood peaks were 29 % and 36 % respectively for the CSM approach, and 39.8 % and 43.6 % respectively for the FEH event-based procedures.

More recently, Lamb *et al.* (2016), provide four examples of practical situations where a CSM approach was required, due to the inability of the standard FEH methods to adequately address the problems. The benefits of using a CSM approach, many of which are identified above, included the physical nature of the model and increased understanding of hydrological processes used to constrain model parameter uncertainty, explicit representation of antecedent conditions and spatial variations in terms of rainfall and runoff, accounting for climate change and land cover change scenarios, explicitly representing flood management operational systems within a CSM, and the ability of the method to provide coherent multivariate flood characteristics. In conclusion Lamb *et al.* (2016) highlights that despite the benefits of the approach and the considerable effort placed on developing national procedures, as reviewed above, a comprehensive national scale CSM approach was never developed, i.e. with standardised data sets and the tools required to easily implement the method. Furthermore, no significant effort was made to promote the uptake of the method in practice and explain why the method remains as a specialist tool to be used only in complex scenarios. Therefore, the critical objective described in Point (ii) above was never achieved.

## 2.6 Design Flood Estimation in Australia

Australian Rainfall and Runoff (ARR) is the national guideline for DFE in Australia (Ball *et al.*, 2016). The first edition of ARR was published in 1958 and has remained one of the most influential and widely used guidelines published by Engineers Australia (Ling *et al.*, 2015). ARR was updated in 1977 and again in 1987/1999, where the 1999 edition is a reprint of the 1987 edition in book form, with only the chapter on the estimation of extreme to large flood events being updated in the 1999 edition. The 1999 edition is often referenced as the 2001 edition, which is simply a reprint of the 1999 edition (Ball *et al.*, 2016). The relatively outdated 1987/1999 edition is currently being revised and updated through 21 research projects to improve on the methodologies used to obtain reliable design flood estimates in Australia (Ball *et al.*, 2016). One of the research projects includes the use of CSM for design flow determination (Project 8), which is reviewed below. The following section, however, contains a review of the primary CSM system for DFE applied practically in Australia (Boughton and Droop, 2003; Ling *et al.*, 2015; Ball *et al.*, 2016), the Continuous Simulation System (CSS) for DFE.

### 2.6.1 Continuous simulation system approach

The CSS for DFE was originally developed by the Cooperative Research Centre for Catchment Hydrology (CRCCH) at Monash University, Melbourne, Australia. A review of CSM for DFE both within Australia and internationally by Boughton and Droop (2003) is a concise and valuable account of the CS models and methods developed and implemented up to 2003. In addition, Droop (2001) reviewed 12 distributed input CS models and 23 event-based models used for DFE. Consequently, only a brief summary of the reviews done by Boughton and Droop (2003) and Droop (2001) is presented and the focus is on more recent developments.

Boughton *et al.* (1999) describe the CSS and Boughton *et al.* ( 2000) tested the CSS on a number of catchments of medium to small sizes in Victoria, Australia, with further experimentation undertaken by Droop and Boughton (2002), who tested a different flood hydrograph model. The components of the CSS include a stochastic rainfall generator, the simple lumped Australian Water Balance Model (AWBM) and a hydrograph model (Ling *et al.*, 2015). Ling *et al.* (2015) and Nathan and Ling (2016) summarise the approach and results obtained by Boughton *et al.* ( 2000) and Droop and Boughton (2002). Ultimately, design values up to the 2000-year return period were estimated and the FFC derived from the method are similar to the observed FFC for the more frequent floods, i.e. up to the 20-year return period (Ling *et al.*, 2015). The CSS was also applied in a large 13 000 km$^2$, semi-arid catchment in Western Australia by Newton and Walton (2000). Further details on CSM approaches to DFE in Australia are reported by, *inter alia*, Boughton and Droop (2003); Pathiraja *et al.* (2012); Ball (2013); Ling *et al.* (2015); Nathan and Ling (2016); and Cu (2016). The following section will focus on some of the most recent work regarding CSM techniques within Australia.

### 2.6.2 ARR revision project 8

Ling *et al.* (2015) report on the developments in *Project 8: Use of Continuous Simulation Models for Design Flood Estimation*; in combination with those of *Project 12: Selection of an Approach*. In summary, the objective of the Ling *et al.* (2015) revision paper is to investigate and compare the performance of traditional Design Event (DE) based, Monte Carlo, and CSM approaches to DFE under a range of conditions. For the CSM component of the study, three separate simple water balance models, widely tested in Australian conditions, were evaluated on four diverse catchments located in various regions across Australia, with an additional catchment added at a later stage. The five catchments selected to evaluate the performance of the CSM approaches were a subset of a total of ten catchments selected to evaluate the performance of the Monte Carlo and DE based approaches (Ling *et al.*, 2015).

The three simple CS rainfall-runoff models used were: (i) the AWBM, as used in the CSS, (ii) the SIMHYD model as detailed by Chiew *et al.* (2002), and (iii) the GR4H model as detailed by Mathevet (2005); van Esse *et al.* (2013) and Bennett *et al.* (2014). For further details on the models refer to Ling *et al.* (2015). Stochastic rainfall generation was not used in the study by Ling *et al.* (2015) since observed input data, i.e. rainfall and potential evapotranspiration, required to simulate streamflow in each of the three models, was available for the same length of available observed flow records for each catchment selected. Furthermore, the objective of the study was to test the ability of the models to reproduce the hydrograph behaviour and the FFC of the observed data and consequently there was no need to stochastically extend the rainfall record. Each of the three models were calibrated to the observed flow data and four different calibration scenarios were investigated, including: (i) calibration to all data, (ii) calibration to a subset of the data, (iii) calibration to flows above a threshold, and (iv) calibration to the observed FFC. A global optimisation algorithm called the Shuffled Complex Evolution (SCE) was used to calibrate the parameters of each of the three models (Ling *et al.*, 2015). In general, the GR4H model provided the best results.

In summary, Ling *et al.* (2015) state that a reasonably good representation of hydrograph behaviour, in conjunction with flood quantiles was only obtained for one out of the five catchments investigated. Therefore, the study highlighted the inability of the CS models used to reproduce both flood hydrographs and flood quantiles consistently across catchments with varying characteristics. It was noted, however, that reasonable results may be obtained given good quality data and adequate model structure (Ling *et al.*, 2015). The findings suggest that CSM models should be calibrated and or configured in different ways for different assessments, *e.g.* if a practitioner is mainly interested in the estimation of accurate flood quantiles the calibration results from the above Scenario (iv) should be utilised. If, however, the practitioner is mainly interested in hydrograph behaviour Scenario (i) should be used. This situation, however, needs to be approached with caution as erroneous results may be obtained when attempting to force a fit. Ultimately, the goal should be to develop models or methodologies that are able to adequately reproduce all aspects of the observed flow data. Therefore, as suggested by Martinez and Gupta (2010) and Ling *et al.* (2015), model performance should be diagnosed in detail and subsequent improvements or refinements to the model should be made.

## 2.7 Additional Continuous Simulation Methods Applied Internationally

The following sections briefly review some additional CSM studies and CS models currently being applied in other countries.

### 2.7.1 The United States

A plethora of CS models have been developed within the United States to date. This section briefly identifies some of the more commonly used CS models applied for DFE in the country. Variations of the Stanford Watershed Model, e.g. the HSPF models, have been used in several studies within the United States for DFE including, inter alia, Soong *et al.* (2005) and Soong *et al.* (2009). Furthermore, Boughton and Droop (2003) make note of a modernised version of the Stanford Watershed Model used in the analysis of design floods for urban catchments. The HSPF models although complex, i.e. with up to 14 parameters to calibrate (Singh *et al.*, 2004), are accepted by the Federal Emergency Agency for use by the National Flood Insurance Program (Soong *et al.*, 2005). The United States Army Corps of Engineers (USACE) Hydrologic Engineering Center – Hydrologic Modelling System (HEC-HMS) is another well-known model, with CSM capabilities, applicable to a wide range of problems for both small urban and natural watersheds. The method has also been used for DFE both in the United States and internationally (Boughton and Droop, 2003; USACE, 2008; Haberlandt and Radtke, 2013; Cu, 2016; USACE, 2016). The Storm Water Management Model (SWMM) developed by USEPA, similar to HEC-HMS, is a dynamic rainfall-runoff simulation model, with CSM capabilities, used to simulate runoff quantity and quality, however, primarily for urban areas (Rossman, 2015). SWMM has also been incorporated into urban drainage models developed in other countries, such as the widely used Danish Hydraulic Institute (DHI), MIKE URBAN software (DHI, 2017). SWMM has also been used for DFE (Ball, 2013; Ahn *et al.*, 2014).

### 2.7.2 France

Paquet *et al.* (2013) describe a probabilistic semi-continuous rainfall-runoff method called *Simulation Climato-Hydrologique pourl'Appréciation des Débits EXtrêmes* (SCHADEX), developed at *Electricité de France* (EDF) for the design of dam spillways. Since its development the SCHADEX method has been extensively utilised both within France, as well as within other European countries, e.g. Norway (Lawrence *et al.*, 2014), for industrial studies, and applied to catchments ranging in size from only a few square kilometres to thousands of square kilometres (Paquet *et al.*, 2013). Paquet *et al.* (2013) explain that the SCHADEX method has replaced the former Gradient of Extreme Values (GRADEX) method as the official method used by EDF to estimate extreme flood discharges for the design of dams. For further details refer to Paquet *et al.* (2013).

Paquet *et al.* (2013) state that the scientific evaluation and development of SCHADEX is ongoing and the method is being compared to other contemporary methods in major projects such as the FloodFreq European Cooperation in Science and Technology (COST) Action (COST, 2013). Several additional CS models are investigated in the FloodFreq European COST Action and a model that is worth mentioning with application to DFE, with considerations of climate change, is the *Hydrologiska Byråns Vattenbalansavdelning* (HBV) model (Bergström, 1976; Bergström, 1992), with several studies referring to or reporting on experimentation with the HBV model for DFE including, inter alia, COST (2013); Devi *et al.* (2015) and Zeng *et al.* (2016).

An additional set of CS models utilised and developed in France include the GR model series, developed under the stewardship of the National Research Institute of Science and Technology for Environment and Agriculture – IRSTEA (Mouelhi *et al.*, 2013). This includes the GR4H model, as implemented in ARR Revision Project 8, which is an hourly version of the GR4J daily rainfall-runoff model developed by Perrin *et al.* (2003) with two storages and four parameters (van Esse *et al.*, 2013; Bennett *et al.*, 2014). Although not a CSM approach, another noteworthy event-based simulation approach – SHYREG, developed over several years also by IRSTEA, has recently been established as a national DFE method in France (Arnaud *et al.*, 2016; Arnaud *et al.*, 2017; Odry and Arnaud, 2017). Arnaud *et al.* (2016); Arnaud *et al.* (2017) and Odry and Arnaud (2017) have compared the SHYREG approach to several other FFA methods applied in the country and highlight several advantages of the approach, including greater stability of the regionalised rainfall-runoff model parameter for different regionalisation methods, in comparison to a regional FFA for example. The method also provides more adequate flood quantiles at higher return periods compared to regionalised statistical approaches including the regional FFA approach, however, overestimates the lower return period events (Odry and Arnaud, 2017). The SHYREG approach utilises a stochastic hourly rainfall generator to simulate extended rainfall time-series, on an event basis, at any point in France at a 1 km resolution. The rainfall-runoff model converts this rainfall into a flood quantile at the point, and these point estimates are scaled to the catchment using reduction factors (Odry and Arnaud, 2017).

### 2.7.3 Italy

In Italy the Research Institute for Geo-Hydrological Protection developed a simple semi-distributed CS model, called *Modello Idrologico Semi-Distribuito in continuo* (MISDc), for flood estimation in the Upper Tiber River (Brocca *et al.*, 2011). The model is composed of two components. The first is a soil water balance model that simulates the soil water content over time as a function of rainfall, infiltration, evapotranspiration and drainage and the second is a modified SCS-*CN* event-based rainfall-runoff model (MISD). Brocca *et al.* (2011) calibrated and validated the MISDc model on three subcatchments within the Upper Tiber River catchment. Using stochastically generated rainfall and temperature data for a period of 5 000 years, Brocca *et al.* (2011) generated a 5 000-year long flow sequence, from which FFCs were derived. The simulations for each subcatchment were repeated ten times to account for the uncertainty and variability associated with the stochastically generated rainfall and temperature inputs. The percentage differences between simulated and observed FFCs ranged between 8 – 13 % for the three subcatchments investigated, confirming the reliability of the method for the estimation of design flood discharges. Similar results and findings are presented by Camici *et al.* (2011). Brocca *et al.* (2011) also highlight the high computational efficiency of the simple MISDc model and conjoining stochastic models, which allow for rapid, accurate and easily obtainable peak discharge estimates for high return periods.

### 2.7.4 Austria

Grimaldi *et al.* (2012) tested an empirical CS procedure named the Continuous Simulation Model for Small and Ungauged Basins (COSMO4SUB), on the gauged Wattenbach River catchment (71 km$^2$), located in the central eastern Alps, Austria. The method is designed for application to small ungauged catchments, particularly where large scale regionalised methods are not applicable. The method comprises of a daily rainfall model and disaggregation method to generate synthetic fine resolution sub-daily rainfall data. Rainfall excess is then estimated using a modified SCS-*CN* loss model (SCS, 1972), which continuously accounts for antecedent soil water using a rainfall separation interval variable ($T_s$). An advanced version of the Width-Function Instantaneous Unit Hydrograph (WFIUH) geomorphological rainfall-runoff model is then used to generate complete hydrographs and peak flows. Finally, a FFA is performed on the peak flow time series to derive Synthetic Design Hydrographs (SDHs) (Grimaldi *et al.*, 2012). The method is relatively simple with only four parameters to be estimated from the physical attributes and characteristics of the catchment. Grimaldi *et al.* (2012) state that the model is capable of providing useful results and is able to simulate a range of flood scenarios, however, further investigation, development and improvement of the approach is necessary.

## 2.8 Discussion and Conclusions

In the past few years there has been a high prevalence of flooding, both in South Africa and internationally, that has caused extensive damage and resulted in the loss of life (Alexander, 2002; Smithers, 2012; UNISDR, 2015; FloodList, 2016). In addition, the effects of climate change are evident in the alterations identified in both the intensity and frequency of extreme rainfall events (Ndiritu, 2005; Kruger, 2006; Hrachowitz *et al.*, 2013; Kusangaya *et al.*, 2014; Kruger and Nxumalo, 2017). Consequently there is a need to modernise, improve and update DFE techniques within South Africa, as outlined in the NFSP. One of the recommendations in the NFSP is further development and assessment of the CSM approach to DFE in South Africa. In addition, the various benefits of a CSM approach to DFE have been highlighted throughout this chapter with international as well as local examples.

The CSM approach may be particularly suited to South Africa for the following reasons. In South Africa climate varies significantly across the country, and significant rainfall variability within relatively small areas is common. Therefore, a CSM approach that accounts for spatial differences in rainfall would be beneficial and appropriate in South Africa. In addition, climate change and land cover change, which are becoming more and more ubiquitous throughout the country, need to be taken into account, and the CSM approach provides an approach to do this in a conceptually sound manner, where parameters can be changed over different time scales to represent these changes. Furthermore, from an operational management perspective, there are a considerable number of dams, water transfer schemes, abstractions (e.g. irrigation), and additional water infrastructure systems that need to be included in FFA, as seen in the example provided by Lamb *et al.* (2016). The CSM approach can incorporate these systems into the analysis, and different scenarios can be simulated, thus providing greater confidence in the results. The strong seasonality of rainfall in certain parts of the country and the wide range of soil types within the country, also suggest that in many cases antecedent conditions play a significant role on runoff response, and therefore the ability of the CSM approach to explicitly account for such conditions is a significant benefit. The CSM approach also has significant potential for use in flood forecasting, as predicted weather information can be used as input into the model to plan for possible flood events before they occur. The forecasting will improve the management of water related infrastructure, e.g. running scenarios on dam releases prior to a flood to prevent overcapacity of the spillway and to minimise risk. Lastly the ability of the method to provide coherent multivariate flood characteristics is a major advantage.

In the development of a national CSM approach to DFE in South Africa, some important lessons can be learnt from the international literature, including the review of the national CSM system developed for the United Kingdom (Calver *et al.*, 2005). For example, it was highlighted that the CSM approach is often neglected in practice as it is more data intensive, complicated and time consuming to apply compared to simple event-based methods. Calver *et al.* (2005), therefore, in the development of the national CSM approach, emphasise the importance of using efficient, yet simple, parameter-sparse CS models, since parameters need to be derived indirectly from easily obtainable catchment descriptors. This is supported by the review of CSM for DFE in Australia where simple parameter-sparse models have been developed and applied. The benefit of the *ACRU* model, however, is that model parameters are not calibrated and transferred to ungauged catchments, instead they are linked to physical catchments characteristics, most of which have been mapped for the country.

The benefit of stochastically generating rainfall time series, for use with a CSM system is also highlighted and strongly recommended in the international review. In addition, the benefit of modelling at a sub-daily time step is also highlighted. Therefore, further development, assessment, and inclusion (i.e. within the CSM approach) of daily rainfall disaggregation and stochastic rainfall generation techniques is strongly recommended for future research, as shown in Table 2.1. These are, however, individually significant research projects in their own right. Consequently, it is proposed that the initial focus should be on the development of a CSM system (Table 2.1), with rainfall disaggregation and stochastically generated rainfall (including climate change considerations, predictions and extrapolations) viewed as secondary, complementary research which could easily be incorporated into the CSM approach.

More recently in South Africa, Rowe (2015) investigated a methodology to include land management and hydrological condition classes used in the SCS-SA model into the *ACRU* land cover classification. Further development and investigation of the approach, however, was recommended including the analysis of additional land cover classes, further independent verification at different geographical locations, and verification of the simulated results against observed data, in terms of both streamflow volumes and peak discharges. In addition, further development of a CSM system or methodology for South Africa was recommended. Confidence in using the SCS-SA classification as a reference, to derive land management practice and hydrological condition classes for use with the *ACRU* model, is gained through the review of contemporary CSM methods applied internationally, i.e. Italy and Austria, where it was highlighted that the SCS-*CN* methodology is still widely applied as accepted practice, but it is evident that this sentiment is not unanimous within the literature.

The next section compiles all the information reviewed thus far and summarises a suggested path towards the establishment of a comprehensive CSM approach for DFE in South Africa.

## 2.9 Recommendations for South Africa

Table 2.1 provides a summary of the steps required to develop and establish a national scale CSM approach for DFE in South Africa. In terms of developing a useable system for practitioners to use, the most critical components from Table 2.1 are Steps 3 and 4. As identified from the review of the developments towards a national CSM approach in the UK (Calver *et al.*, 2005), and as highlighted by Lamb *et al.* (2016), this was the critical step that was not achieved. Therefore, the successful adoption of this approach will rely on the development of a final software tool, with all the necessary inputs and national scale databases required. The idea, as alluded to in Table 2.1, is to base the system (particularly in terms of the user interface and options) on the already widely used SCS-SA event-based approach, which should greatly assist in the adoption of the approach in practice. In addition, while working on the *ACRU* CS model, it has been proposed to use the results and range of simulation outputs from the *ACRU* model to update the soil water adjustment options in the SCS-SA model. The standard and updated options should be used with the SCS-SA model and comparative studies performed against the final CSM system established. Additional comparisons with other DFE methods may also be considered and are encouraged in future.

Table 2.1 Steps required to develop a comprehensive useable CSM approach for DFE in South Africa

| **STEP 1** |
|---|
| Further development, validation and verification of the *ACRU* CS model in terms of:<br>• Input data (climate, soils, land cover), model structure in terms of process representation, and how best to set up or package the model in terms of ease of use, while still providing outputs of high quality and certainty, i.e. level of detail required.<br>• Accurate simulations of both day-to-day flows and extreme values - in terms of volumes, peak discharges (Lag time) and complete hydrographs.<br>• The inclusion of a methodology to account for uncertainty in model parameterisation. |
| **STEP 2** |
| Further development, assessment and inclusion of national stochastic rainfall generation and / or disaggregation techniques:<br>• These methods will introduce the ability to account for uncertainty in model time-series inputs, as well as increase confidence in estimates of high return period events (100 years and above).<br>• The methods should also provide options to estimate projected climate change scenarios, or alternatively an additional set of rainfall models should be established for this. These techniques will be of significant benefit to both the CSM approach as well as other event-based simulation approaches. |
| **STEP 3** |
| • Compiling all these steps and additional models into a user-friendly, simple software tool, that is attractive to consultants and government organisations (e.g. DWS, SANRAL).<br>• Training courses, workshops and user manuals are critical to successful adoption of the approach, however, if the model options are similar to an already widely used tool, i.e. the SCS-SA model, this will greatly facilitate adoption of the approach in practice**.** |
| **STEP 4** |
| • Continual updating, refinement and improvement of the approach including, for example, flood routing routines and flood forecasting.<br>• Close collaboration between practitioners and model developers (researchers) is needed. |

In addition, it is important to note at this stage that it is the author's opinion that the *ACRU* CS model has significant potential, since it has been adapted to South African conditions and has been extensively validated and verified, and is therefore a suitable comprehensive CS model to be used in future studies. There should, however, also be evaluation of the performance of simpler, parameter sparse CS models for DFE in South Africa.

Therefore, in summary, the potential for using a CSM approach to DFE in South Africa is evident from studies reported in the literature. However, there is still significant development required before a CSM system for DFE can be widely used by practitioners and it is recommended that the steps summarised in Table 2.1 should be followed.

# 3. DEVELOPMENT OF AN IMPROVED COMPREHENSIVE CONTINUOUS SIMULATION MODELLING SYSTEM FOR DESIGN FLOOD ESTIMATION IN SOUTH AFRICA USING THE *ACRU* MODEL

This chapter provides some background to previous developments towards a Continuous Simulation Modelling (CSM) approach for Design Flood Estimation (DFE) in South Africa, and describes the development of a comprehensive CSM system that builds on the previous developments. This includes the structure of the system, how to implement the system and the default input information to use with the system, i.e. when site-specific information is not available.

## 3.1 Introduction

As reviewed in Chapter 2, the methods applied for DFE in South Africa are dated. Consequently a National Flood Studies Programme (NFSP), aimed at updating these methods, has recently been proposed and initiated (Smithers *et al.*, 2016). One of the recommendations of the NFSP is to further develop and assess a CSM approach for DFE in South Africa. To date, reasonable results have been obtained applying the daily time-step *ACRU* agro-hydrological Continuous Simulation (CS) model (Schulze, 1995), in a number of pilot studies (Smithers *et al.*, 1997; Smithers *et al.*, 2001; Chetty and Smithers, 2005; Smithers *et al.*, 2007; Smithers *et al.*, 2013). More recently, Rowe *et al.* (2018) developed an approach to parameterise the *ACRU* CS model for DFE within South Africa, to explicitly represent land management practices and hydrological conditions for a range of land cover classes defined in the SCS-SA land cover classification, which are not represented, or not adequately represented, in the *ACRU* land cover classification, as detailed below. The SCS-SA land cover classification was derived from the original SCS (1956) classification, and adapted to South African conditions to produce a table of *CN*s for selected, natural, agricultural, suburban and urban land cover classes (Schmidt and Schulze, 1987a). An example of typical land management practice and hydrological condition classes defined in the SCS-SA land cover classification is provided in Table 3.1 for Row Crops, e.g. maize. As reported by Schmidt and Schulze (1987a), hydrological condition is represented by stormflow potential (Table 3.1), i.e. a high stormflow potential is indicative of a land cover class in poor hydrological condition (< 50% plant cover) and low stormflow potential a land cover class in good hydrological condition (> 75% plant cover). In the SCS-SA adaptation of the SCS (1956) land cover and soils classification, the concept used to define soils into hydrological soil groups is slightly different and the number of soil groups was increased from four to seven (Table 3.1), in order to accommodate the wide range of soil types found in South Africa (Schmidt and Schulze, 1987a; Schulze, 2012). Group A soils have the highest infiltration and permeability characteristics and *vice versa* for Group D soils.

Table 3.1 Initial *CN*s for Row Crops for specific land management practice, hydrological condition, and soil group 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** |
| 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 |

The most comprehensive land cover classification available for use with the *ACRU* model is the COMPOVEG database (Schulze, 1995; Smithers and Schulze, 2004). The COMPOVEG database contains default assigned parameter values required by the *ACRU* model to represent 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 3.1.

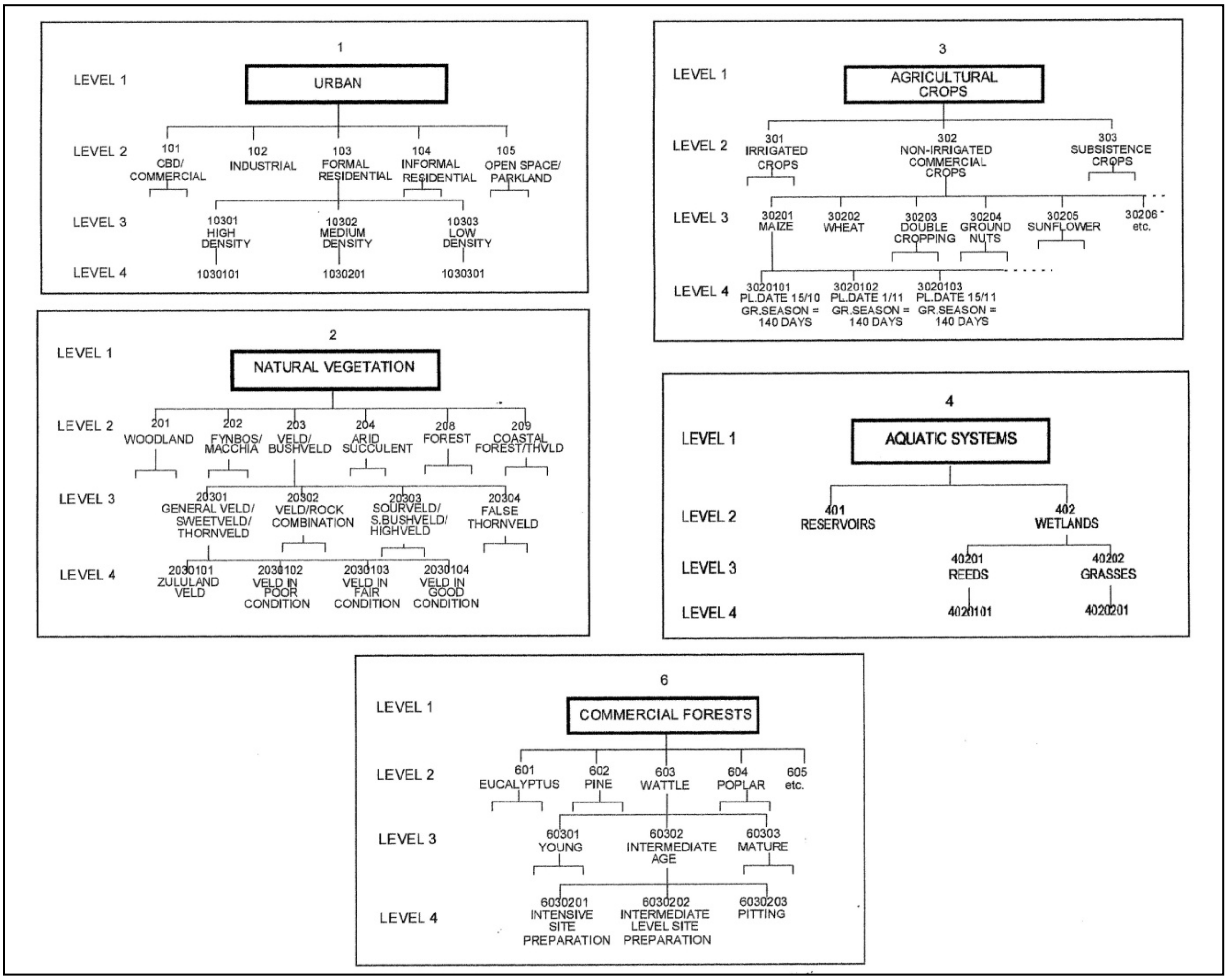

Figure 3.1 The four-level structure of the land cover/land use classification developed for the *ACRU* model (Schulze, 1995)

The land cover classification does not explicitly account for land management practices associated with agricultural crops, as accounted for in the SCS-SA classification (Table 3.1). Since the *ACRU* model is a daily timestep CS model, the land cover classification does account for different crop development stages, i.e. from planting to harvest, and accounts for regional differences in planting dates for specific dominant crops cultivated extensively in different parts of the country, such as maize and wheat (Figure 3.1). The classification also distinguishes between commercial and subsistence crops, however, does not explicitly represent the land management practice and hydrological condition for each. In terms of natural vegetation, the classification includes classes to represent good, fair and poor hydrological condition for selected land cover classes such as veld (grassland). This, however, is not consistently represented for all natural land cover classes. Furthermore, Rowe *et al.* (2018) identified that the *ACRU* model is insensitive to the parameters adjusted and used to represent the different hydrological condition classes, in terms of design flood estimates. This was particularly concerning, based on the comparative changes in stormflow response simulated by the SCS-SA model for similar changes in hydrological condition for similar land cover classes. Rowe *et al.* (2018) therefore, performed a sensitivity analysis of the *ACRU* model to selected parameters to identify which parameters to use, to more adequately represent the change in stormflow response for different land management practices and hydrological conditions. It is important to reiterate that, in this study, the assumption has been made that the hydrological responses simulated by the SCS-SA model, through the CN, for the range of land cover classes defined in the SCS-SA land cover classification, are reasonable and representative of these land cover classes. The reliance on the SCS-SA model and associated CNs is attributed to the absence of observed data on hydrological responses from land cover classes and soil combinations as defined in the SCS-SA land cover classification. Further justification for the use of the results simulated by the SCS-SA model, i.e. as a surrogate for observed data to simulate similar magnitudes and changes in stormflow response in *ACRU*, is gleaned from the fact that the *CN*s adopted in the SCS-SA model were at least calibrated using observed data for a range of land cover / soil conditions (Mishra and Singh, 2003). Rowe *et al.* (2018) identified two parameters to represent land management practice and hydrological condition in the *ACRU* model, namely: (i) the Quick Flow Response Coefficient (*QFRESP*) which partitions stormflow into a same day response fraction and a subsequent delayed stormflow response, and (ii) the Critical Hydrological Response Depth of the Soil (*SMDDEP*). These parameters are currently generally set to recommended default values, however, some guidance on the selection of SMDDEP is provided in the *ACRU* Theory Manual on the basis of vegetation density, soil conditions, climate and rainfall intensity (Schulze, 1995). Rowe *et al.* (2018), however, developed a consistent methodology to parameterise these two parameters using SCS-SA *CN*s. Consequently, linking both of these parameters to physically measurable soils and land cover characteristics of a catchment, including land management practices and hydrological conditions. For context, a summary of the methodology applied by Rowe *et al.* (2018) is provided in the section to follow.

The objectives of this chapter are to: (i) build on the investigations and results of Rowe *et al.* (2018), and (ii) to incorporate these developments into a comprehensive CSM system for DFE in South Africa. The idea is to start with a simple system similar to, and based on, the SCS-SA model (Schulze *et al.*, 2004), in order to facilitate migration from the SCS-SA approach to the

*ACRU* CSM approach in practice. The objective is in line with recommendations from the international literature as reviewed in Chapter 2, *e.g.* the United Kingdom and Australia, of simplicity and user friendliness, while still providing accurate results. It is hypothesised that a system that incorporates the valuable information calibrated into the *CN* along with explicit soil water budgeting will provide the most accurate results when simulating flows for different land cover and soil combinations. Additional motivation lies in the realisation that the SCS-*CN* method is still widely used (Brocca *et al.*, 2011; Grimaldi *et al.*, 2012; Rossman, 2015; USACE, 2016).

## 3.2 Parameterisation of the *ACRU* Model for DFE

As described in Section 3.1, Rowe *et al.* (2018) identified that land management practices and hydrological conditions are not adequately represented in the *ACRU* model, as represented in the SCS-SA model. Consequently, Rowe *et al.* (2018) developed a methodology to represent SCS-SA land cover classes within the *ACRU* model. This was achieved by using the design stormflow volumes simulated by the SCS-SA model as a surrogate for observed data. For context, this section summarises the methodology applied and results obtained by Rowe *et al.* (2018). The first step undertaken by Rowe *et al.* (2018) was to identify how to represent SCS-SA soil groups (A – D) in the *ACRU* model. Three different approaches were applied using soil textural properties to represent SCS-SA soil groups, however, these approaches alone were unsuccessful. Consequently, a sensitivity analysis of the *ACRU* model to several parameters was conducted in order to identify which parameters to use to represent SCS-SA soils and associated *CN*s best, for selected land cover classes. Two *ACRU* parameters, namely: (i) *QFRESP*, a Quick Flow Response Coefficient which partitions stormflow into a same day response fraction and a subsequent delayed stormflow response, and (ii) *SMDDEP*, which determines the critical hydrological response depth of the soil, were identified as sensitive parameters suitable to represent SCS-SA soils and land cover classes. Through manual calibration *QFRESP* and *SMDDEP* parameter values, corresponding to a SCS-SA soil group and land cover class, were identified to represent that land cover class in *ACRU*. This was achieved by adjusting the *QFRESP* and *SMDDEP* parameters in the *ACRU* model until similar stormflow volumes to those simulated by the SCS-SA model were obtained for a similar land cover class in *ACRU* (Rowe et al., 2018).

Applying a multiple linear regression, a strong relationship between these two *ACRU* parameters and SCS-SA *CN* values was obtained and consequently preliminarily rules and equations were developed to represent SCS-SA land cover classes in *ACRU*. The multiple linear regression, however, was skewed by the results obtained for SCS-SA soil Group C/D, therefore a separate multiple linear regression analysis was performed for soil Group C/D (Rowe et al., 2018).

Equation 3.1 (Rowe et al., 2018) was derived from the multiple linear regression for all SCS-SA land cover classes for all SCS-SA soil groups, excluding SCS-SA soil Group C/D, to estimate "predicted" *CN* ($CN_p$) values for given *QFRESP* and *SMDDEP* combinations as calibrated against actual tabulated SCS-SA *CN* values.

$$CN_p = 43.91(QFRESP) - 75.52(SMDDEP) + 53.78 \tag{3.1}$$

The $CN_p$ values were then compared to the actual tabulated SCS-SA *CN* values. Based on the good correlation obtained between the $CN_p$ values and the actual tabulated SCS-SA *CN* values, Equation 3.1, was used to develop rules to estimate *QFRESP* and *SMDDEP* parameter values for tabulated SCS-SA *CN* values. These rules, for all SCS-SA soil groups, excluding SCS-SA soil Group C/D, are provided in Table 3.2.

The rules as summarised in Table 3.2 are explained as follows (Rowe et al., 2018). Rules were developed for different *CN* ranges. The first range of *CN* values being those ranging from 40 – 48. For this range of *CN* values, the rules state that a fixed *QFRESP* value of 0.3 must be used and Equation 3.1 rearranged to solve for *SMDDEP*. An example is shown in Table 3.2 where an estimated *SMDDEP* value of 0.28 is calculated for an input *CN* value of 46, after rearranging Equation 3.1 to solve for *SMDDEP*. It was recommended by Rowe *et al.* (2018) that *CN* values lower than 40 should not be simulated in general, since the *SMDDEP ACRU* parameter value below a *CN* value of 40 starts increasing to depths not within the range recommended for use within the *ACRU* model. The rules in Table 3.2 for the *CN* range of 40 – 48 may, however, be applied for *CN* values below 40 for catchments with extremely low stormflow potential. Extrapolation to *CN* values below 30, however, is not recommended, and is the absolute minimum threshold. These recommendations are in line with SCS (SCS, 1956) and SCS-SA (Schmidt and Schulze, 1987a) convention, where use of a *CN* value below 50, particularly for

DFE, is not recommended. Therefore, if a *CN* value below 40 is identified for a catchment, it is recommended to use a value of 40, unless the catchment has extremely low stormflow potential, where a value between 30 and 40 may be selected by experienced users. For *CN*s ranging from 48 – 79, the rules state that *SMDDEP* must remain fixed at a value of 0.25 and Equation 3.1 must be rearranged in order to solve for *QFRESP*. An example is shown for a *CN* value of 79, where the *QFRESP* value is calculated to be 1.00. If a *CN* value of 48 is identified for a catchment the rules for *CN* range 40 – 48 or 48 – 79 may be used and will provide the same result, as this is a transition point. For *CN* values greater than 79, the rules state that *QFRESP* must remain fixed at 1.00 and Equation 3.1 must be rearranged in order to once again solve for *SMDDEP* (Rowe et al., 2018).

Table 3.2 Rules developed for all SCS-SA soil groups, excluding SCS-SA soil Group C/D (Rowe et al., 2018)

| **Rules** | ***CN* 40 - 48** | ***CN* 48 - 79** | ***CN* > 79** |
|---|---|---|---|
| | ***QFRESP* = 0.3** | ***SMDDEP* = 0.25** | ***QFRESP* = 1** |
| Input *CN* | 46 | 79 | 82 |
| Rearrange Equation 3.1 to solve for *SMDDEP or QFRESP* | *SMDDEP* | *QFRESP* | *SMDDEP* |
| Calculated value | 0.28 | 1.00 | 0.21 |

Equation 3.2 (Rowe et al., 2018) was derived to estimate $CN_p$ values for given *QFRESP* and *SMDDEP* combinations for all SCS-SA land cover classes for SCS-SA soil Group C/D:

$$CN_p = 32.92(QFRESP) - 48.28(SMDDEP) + 63.91 \tag{3.2}$$

In addition, the rules presented in Table 3.3 were determined for SCS-SA soil Group C/D and are interpreted in the same manner as the results from Table 3.2 (Rowe et al., 2018). The value of *QFRESP* cannot be greater than 1, therefore the value of 1.01 in Table 3.3 should be taken as 1. The value of 1.01 in Table 3.3 is an artefact of the regression equation (Equation 3.2).

Table 3.3 Rules developed for SCS-SA soil Group C/D only (Rowe et al., 2018)

| **Rules** | ***CN* 57 - 62** | ***CN* 62 - 85** | ***CN* > 85** |
|---|---|---|---|
| | ***QFRESP* = 0.3** | ***SMDDEP* = 0.25** | ***QFRESP* = 1** |
| Input *CN* | 62 | 85 | 88 |
| Rearrange Equation 3.2 to solve for *SMDDEP or QFRESP* | *SMDDEP* | *QFRESP* | *SMDDEP* |
| Calculated value | 0.24 | 1.01* | 0.18 |
| * Value cannot be greater than 1 therefore if greater than 1 change to 1 | | | |

The rules defined by Rowe *et al.* (2018) above were only developed and assessed using design stormflow volumes and not peak discharges. Furthermore, the results were not verified against observed data. Therefore further development and assessment of the approach was highly recommended by Rowe *et al.* (2018). This included further development of a comprehensive CSM system for DFE in South Africa, and verification of the system performance against observed data in terms of both simulated streamflow volumes and peak discharges. The next section addresses the first recommendation listed above, i.e. further development of a comprehensive CSM system for DFE in South Africa using the *ACRU* model. This includes defining a complete structure of the system, default datasets and classifications to use with the system, and model options. The performance of the comprehensive CSM system developed is then assessed in subsequent chapters.

## 3.3 Development of a Comprehensive CSM System for DFE using the *ACRU* Model

In order to develop a comprehensive CSM system for DFE using the *ACRU* model, the following steps were performed:

(i) Select and define default model input information to use with the *ACRU* CSM system for DFE. Consequently, the following default datasets were selected:
  - Rainfall and climate files – the default input rainfall and climate data assigned per quinary, and stored in the Quinary Catchments Database (Schulze and Horan, 2010) was selected. Alternatively, high quality rainfall data from other sources such as research catchments and the Lynch (2003) database should be used. The raingauge that is most representative of the catchment under investigation must always be used.

- Soils - soils are represented by SCS-SA soil groups, as applied in the SCS-SA method, and obtained from sources such as:
    - the literature, *i.e.* where detailed soils analyses have been conducted (generally restricted to research catchments),
    - the Land Type maps (SIRI, 1987), or
    - from maps of SCS-SA soil groups for South Africa, as developed by Schulze (2012) and an updated map (Schulze and Schütte, 2018) which factors in terrain units. Owing to their national coverage these data sources were selected as the default. However comparison with the other data sources, where available or feasible, was performed as this provides a way of validating the accuracy of the maps.

  The SCS-SA soil group and land cover class is used to parameterise the *ACRU QFRESP* and *SMDDEP* parameters, as detailed below. In terms of the general *ACRU* soil property inputs, e.g. topsoil and subsoil depths, permanent wilting point, field capacity, porosity and soil horizon response fractions, values assigned as per SCS-SA soil group by the Binomial Soil Classification approach (Rowe, 2015), as summarised in Table 3.4, were used as the defaults for these soil input parameters.
- Land cover - the National Land Cover dataset of 2000 (ARC and CSIR, 2005), referred to as NLC 2000 from this point on, and an updated 2013/2014 version (DEA and GTI, 2015), referred to as NLC 2013/2014 from this point on, are the most comprehensive national coverages of actual land cover in South Africa. This land cover information is a suitable baseline and is used in the CSM system as the default land cover information, unless more detailed information is available, *i.e.* particularly relevant to research catchments, where the vegetation coverage has been explicitly described and documented.

Table 3.4 Default *ACRU* soils input information assigned to SCS-SA soil groups by Rowe (2015)

| **Parameter** | **SCS-SA Soil Group** | | | | | | |
|---|---|---|---|---|---|---|---|
| | **A** | **A/B** | **B** | **B/C** | **C** | **C/D** | **D** |
| *DEPAHO* (m) | 0.250 | | | | | | |
| *DEPBHO* (m) | 0.500 | | | | | | |
| *WP1* and *WP2* (m.m$^{-1}$) | 0.096 | 0.112 | 0.126 | 0.142 | 0.153 | 0.209 | 0.153 |
| *FC1* and *FC2* (m.m$^{-1}$) | 0.181 | 0.200 | 0.217 | 0.233 | 0.248 | 0.308 | 0.246 |
| *PO1* and *PO2* (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 |
| Default texture class | Sandy loam [5] | | | Sandy clay loam [7] | | | |

*DEPAHO* - Depth of the topsoil, *DEPBHO* - Depth of the subsoil, *WP1* - Permanent Wilting Point (topsoil), *WP2* - Permanent Wilting Point (subsoil), *FC1* - Field Capacity (topsoil), *FC2* - Field Capacity (subsoil), *PO1* - Porosity (topsoil), *PO2* - Porosity (subsoil), *ABRESP* - Fraction of soil water above *FC1* that drains from the topsoil into the subsoil, *BFRESP* - Fraction of soil water above *FC2* that drains from the subsoil into the intermediate groundwater zone

(ii) Using the default land cover data, a comprehensive land cover classification for use with the *ACRU* model, similar to the SCS-SA classification, with the parameters required to model each of the NLC 2000 and NLC 2013/2014 land cover classes was developed as follows:

- Based on the rules developed by Rowe *et al.* (2018), as described in Section 3.2 above, a final land cover classification for use with the *ACRU* model was established. The classification was adopted from the SCS-SA land cover classification (Schulze *et al.*, 2004), with modifications in order to make the classification more compatible with the NLC 2000 and NLC 2013/2014 land cover classes, as detailed in the next section.
- Appropriate land cover classes from the final *ACRU* land cover classification were assigned to each of the 49 different land cover classes of the NLC 2000 dataset and the 72 classes of the NLC 2013/2014 dataset, in order to model these default selected land cover classes.

(iii) A structure of how to apply the model, i.e. level of detail and model options, was then established to provide a consistent methodology to implement the approach.

The following sections provide further details on Steps (ii) and (iii).

### 3.3.1 Revised land cover classifications and mapping to NLC

As mentioned above, a revised SCS-SA land cover classification (Schulze *et al.*, 2004) was developed and used to establish a final land cover classification for use with the *ACRU* model. Some modifications and additions to the original SCS-SA land cover classes were made in order to make the final classification more compatible with the land cover classes of the NLC 2000 (Table 12.1) and NLC 2013/2014 (Table 13.1) classifications, i.e. since these maps were selected as the default land cover information to use when more detailed or site-specific information is not available. An example of the original SCS-SA land cover classification (Schulze *et al.*, 2004) for a veld (range) and pasture land cover class is given in Table 3.5.

Table 3.5 Veld (range) and pasture land cover class from the original SCS-SA land cover classification (Schulze et al., 2004)

| **SCS Class** | **Treatment** | **Hydrological Condition** | **Hydrological Soil Group** | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | | | **A** | **A/B** | **B** | **B/C** | **C** | **C/D** | **D** |
| Veld (range) and pasture | 1 = Veld/pasture in poor condition | Poor | 68 | 74 | 79 | 83 | 86 | 88 | 89 |
| | 2 = Veld/pasture in fair condition | Fair | 49 | 61 | 69 | 75 | 79 | 82 | 84 |
| | 3 = Veld/pasture in good condition | Good | 39 | 51 | 61 | 68 | 74 | 78 | 80 |
| | 4 = Pasture planted on contour | Poor | 47 | 57 | 67 | 75 | 81 | 85 | 88 |
| | 5 = Pasture planted on contour | Fair | 25 | 46 | 59 | 67 | 75 | 80 | 83 |
| | 6 = Pasture planted on contour | Good | 6 | 14 | 35 | 59 | 70 | 75 | 79 |

In the revised SCS-SA classification, the original SCS-SA veld (range) and pasture land cover class (Table 3.5) has been separated into individual classes, one explicit class for pasture and one for veld, with the latter renamed Unimproved (Natural) Grassland (Table 3.6). In the NLC 2000 (Table 12.1) and NLC 2013/2014 (Table 13.1) classifications, the most representative land cover classes for veld are Unimproved (Natural) Grassland (NLC 2000) and Grassland (NLC 2013/2014). Since the NLC 2000 classification is more descriptive and distinguishes between natural grassland, i.e. Unimproved (Natural) Grassland, and improved grassland, i.e. Improved Grassland (Planted Grassland), the veld land cover class was renamed to Unimproved (Natural) Grassland. As seen from Table 3.6 the Unimproved (Natural) Grassland class has the same *CN* values as the previous veld (range) and pasture land cover class (Table 3.5), i.e. for the veld/pasture sub-classes. Therefore, the *CN* values of the veld class have not changed, the class is just explicitly represented and has been renamed.

Table 3.6 Example of revised SCS-SA Veld (Unimproved (Natural) Grassland) and Pasture land cover classes

| SCS Class | Treatment / Class Type | Hydrological Condition | Hydrological Soil Group | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | | | A | A/B | B | B/C | C | C/D | D |
| Unimproved (Natural) Grassland | 1 = in poor condition | Poor | 68 | 74 | 79 | 83 | 86 | 88 | 89 |
| | 2 = in fair condition | Fair | 49 | 61 | 69 | 75 | 79 | 82 | 84 |
| | 3 = in good condition | Good | 39 | 51 | 61 | 68 | 74 | 78 | 80 |
| Pasture | 1 = in poor condition | Poor | 68 | 74 | 79 | 83 | 86 | 88 | 89 |
| | 2 = in fair condition | Fair | 49 | 61 | 69 | 75 | 79 | 82 | 84 |
| | 3 = in good condition | Good | 39 | 51 | 61 | 68 | 74 | 78 | 80 |
| | 4 = planted on contour | Poor | 47 | 57 | 67 | 75 | 81 | 85 | 88 |
| | 5 = planted on contour | Fair | 25 | 46 | 59 | 67 | 75 | 80 | 83 |
| | 6 = planted on contour | Good | 6 | 14 | 35 | 59 | 70 | 75 | 79 |

In order to parameterise the *ACRU* model for each of the revised SCS-SA land cover classes developed, a representative *ACRU* land cover class, i.e. from the COMPOVEG database, had to be assigned to each of the revised SCS-SA land cover classes. As an example, Table 3.7 indicates the *ACRU* land cover class assigned to the revised SCS-SA Unimproved (Natural) Grassland class in good condition. The selected *ACRU* land cover class, UNIMPROVED GRASSLAND (COMPOVEG number 5060103), retains all the parameter values assigned to this class from the COMPOVEG database (Schulze, 1995; Smithers and Schulze, 2004; Schulze, 2013), i.e. as required to model this land cover class in *ACRU*. These include parameter values to account for rainfall interception, initial abstractions, evapotranspiration rates, and rooting depths for the selected land cover class. The *QFRESP* and *SMDDEP* parameters, however, which are usually set to default values, have been parameterised based on the *CN*s assigned to the revised SCS-SA land cover class, to which the *ACRU* land cover class has been assigned, as indicated in Table 3.7. The *QFRESP* and *SMDDEP* parameter values were parameterised applying the rules developed by Rowe *et al.* (2018).

Table 3.7 Example of an *ACRU* land cover class assigned to a revised SCS-SA class, and *QFRESP* (QF) and *SMDDEP* (SM) parameter values assigned to SCS-SA *CN*s

<table>
<tr><th rowspan="2">SCS Class</th><th rowspan="2">Treatment (condition)</th><th colspan="14">Hydrological Soil Group</th></tr>
<tr><th colspan="2">A</th><th colspan="2">A/B</th><th colspan="2">B</th><th colspan="2">B/C</th><th colspan="2">C</th><th colspan="2">C/D</th><th colspan="2">D</th></tr>
<tr><td>Unimproved (Natural) Grassland</td><td>3 = in good condition</td><td colspan="2">39</td><td colspan="2">51</td><td colspan="2">61</td><td colspan="2">68</td><td colspan="2">74</td><td colspan="2">78</td><td colspan="2">80</td></tr>
<tr><th colspan="2"><i>ACRU</i> Land Cover Class</th><th>QF</th><th>SM</th><th>QF</th><th>SM</th><th>QF</th><th>SM</th><th>QF</th><th>SM</th><th>QF</th><th>SM</th><th>QF</th><th>SM</th><th>QF</th><th>SM</th></tr>
<tr><td colspan="2">UNIMPROVED GRASSLAND (5060103)</td><td>0.30</td><td>0.37</td><td>0.37</td><td>0.25</td><td>0.59</td><td>0.25</td><td>0.75</td><td>0.25</td><td>0.89</td><td>0.25</td><td>0.79</td><td>0.25</td><td>1.00</td><td>0.23</td></tr>
</table>

The complete revised SCS-SA classification, with assigned *ACRU* land cover classes, is provided in Table 10.1. Details and examples of how and why each of the *ACRU* land cover classes were assigned is provided in Section 3.3.2 and Chapter 14. A final *ACRU* land cover classification, similar to the SCS-SA classification, with *CN*s translated into *QFRESP* and *SMDDEP ACRU* parameter values, based on the rules developed by Rowe *et al.* (2018), is provided in Table 11.1. The land cover classes of the final *ACRU* land cover classification retain the name of those defined within the revised SCS-SA classification, in an attempt to facilitate migration from the SCS-SA method to the *ACRU* CSM system being developed. Default land cover classes, from this final *ACRU* land cover classification (Table 11.1) were then assigned to each of the 49 land cover classes identified in the NLC 2000 classification and 72 classes of the NLC 2013/2014 classification, as summarised in Table 12.1 and Table 13.1, respectively.

The following section provides details on how the CSM system and associated *ACRU* model were configured, and should be reviewed with reference to Table 10.1 - Table 13.1.

### 3.3.2 Model configuration for the *ACRU* CSM system developed

The following model configuration has been defined for the CSM system, based on a similar system developed and proposed by Schulze (2013). Depending on the land cover classes identified within a catchment, the catchment is sub-delineated into no more than five land cover determined Hydrological Response Units (HRUs) or special cases. HRUs are defined areas within a catchment that have the same properties in terms of soils and land cover information, i.e. with a similar hydrological response. Within the model, HRUs are not spatially explicit, *i.e.* polygons with the same land cover within a catchment are aggregated and simulated as one spatial unit. Furthermore, HRUs are not of equal area, *i.e.* the area of each HRU is dependent on the percentage of the area covered by each of the five most dominant HRUs. However, when added together the HRUs make up the total catchment area (Schulze, 2013). Each HRU is modelled as an entity, thus facilitating the impacts of individual land cover classes to be assessed, with their outputs available as a daily file or as statistical summaries, but at the catchment outlet the accumulated effects of all upstream land cover classes can also be assessed (Schulze, 2013). The HRUs are hydrologically inter-connected conceptually, as illustrated in Figure 3.2. The defined limit of delineation into no more than five HRUs is based on practicality and was considered reasonable for the CSM system developed. The selection of five HRUs is based on the recommendations of Schulze (2013) on modelling quinary catchments, realising that some catchments may contain fewer than five land cover classes within them, while many may contain more than five. However, in many cases some land cover classes make up very small areas of the catchment and therefore their hydrological influence may be considered negligible or insignificant. Therefore, it is considered reasonable to assign these small areas to the most dominant natural land cover class.

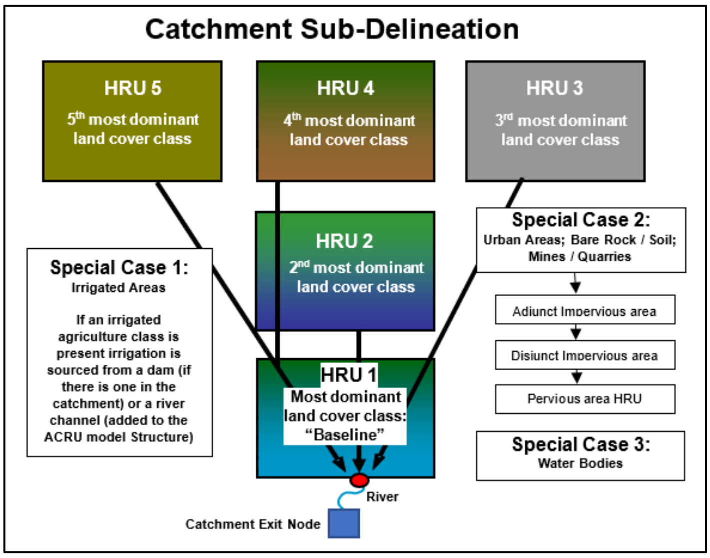

Figure 3.2 Sub-delineation of a catchment into HRUs based on land cover information (after Schulze, 2013)

The HRUs and special cases are configured as follows:

(i) Firstly, the most dominant land cover class, referred to as the "Baseline" HRU, is identified from the NLC 2000 or NLC 2013/2014 shapefiles/rasters, unless more detailed land cover information is available. In many cases this will be a natural land cover class, however, it may be any of the land cover classes defined in the NLC 2000 or NLC

2013/2014 shapefiles/rasters, or as identified from site-specific information. This HRU is referred to as the Baseline since any land cover classes identified within the catchment that are not one of the five most dominant land cover classes are lumped together with this Baseline HRU.

(ii) In order to verify the performance of the CSM system developed against observed data, accurate representation of land cover information for the simulation period is essential. Since the observed record lengths of many gauged catchments within the country do not extend beyond the year 2000, it was considered important to include the NLC 2000 dataset within the system, since this is the best information available to represent actual land cover up to the year 2000. Once the system has been verified, simulations using the most up to date land cover (NLC 2013/2014) may be used to predict streamflow responses for current conditions. The provision of both datasets also provides the opportunity to compare the changes in streamflow response simulated by the model for associated land cover changes, identified from the NLC maps.

(iii) Up to four additional HRUs, or special cases, may be selected based on the diversity of land cover within the catchment being investigated, and the percentage of the area covered by each land cover. These additional HRUs are selected in order of decreasing dominance by area, i.e. the second most dominant land cover after the baseline, followed by the third most dominant and so forth. Dominant land cover classes are defined as land cover classes that account for at least 10%, and 5% for forest plantations, of the total catchment area. This can include any of the NLC 2000 or NLC 2013/2014 land cover classes (Table 12.1 and Table 13.1) or, if more detailed information is available, any of the land cover classes defined in the final *ACRU* land cover classification developed (Table 11.1). Land cover classes that are not identified as dominant land cover classes are lumped together with the baseline HRU, as described above. Added together the HRUs make up the total catchment area.

(iv) Every land cover class selected from the final *ACRU* land cover classification (Table 11.1), or as assigned to the NLC 2000 or NLC 2013/2014 classes (Table 12.1 and Table 13.1), requires a representative SCS-SA soil group to determine the *QFRESP* and *SMDDEP ACRU* parameter values, as well as additional soil properties (Table 3.4). If detailed soils information for the catchment is not available from the literature or other sources, the SCS-SA soil group for the catchment under investigation is determined from maps of SCS-SA soil groups for South Africa, developed by Schulze (2012) and an updated map (Schulze and Schütte, 2018) which factors in terrain units. A single area weighted SCS-SA soil group for the catchment is used.

(v) Evapotranspiration Option 1 in the *ACRU* model is applied for all HRUs, *i.e.* Soil Water Evaporation (*Es*) and Plant Transpiration (*Et*) are calculated as an entity. This option was selected to eliminate the additional complexity of including and explicitly representing the Percentage Surface Cover (*PCSUCO*), with parameter values not yet defined for certain land cover classes, as required when using evapotranspiration Option 2. For evapotranspiration Option 2, *Es* and *Et* are calculated separately and the fraction of *Es* is dependent on the *PCSUCO*. Further details relating to the evapotranspiration options in the *ACRU* model are detailed in Schulze (1995).

(vi) Since the NLC 2000 and NLC 2013/2014 land cover databases (Table 12.1 and Table 13.1) were selected as the default land cover information for use with the *ACRU* CSM system, and since they cover the full range of general land cover classes available in the final *ACRU* land cover classification (Table 11.1), they are used to outline how to model each of the land cover classes in the final *ACRU* land cover classification (Table 11.1), as detailed in the following sub-sections.

#### 3.3.2.1 Modelling natural land cover classes

The natural land cover classes of the NLC 2000 database, i.e. Classes 1 – 6 and Classes 18 – 22 (still considered to be natural land cover classes, however, in a degraded condition), as summarised in Table 12.1, and NLC 2013/2014 database, i.e. Classes 4 – 9, as summarised in Table 13.1, are modelled using the default final *ACRU* land cover classes assigned, as selected from Table 11.1, unless more detailed information is available. Examples of how the final *ACRU* land cover classes were assigned to each of the natural land cover classes of the NLC 2000 and NLC 2013/2014 databases (Table 12.1 and Table 13.1) is provided in Appendix E (Chapter 14). If one of these natural land cover classes is identified as one of the dominant HRUs, it is modelled as an individual HRU, in addition to any other dominant HRUs identified, i.e. which may include additional natural land cover classes or non-natural land cover classes, as described in the next section.

#### 3.3.2.2 Modelling non-natural land cover classes

Non-natural land cover classes in the NLC 2000 database include: (i) improved grassland (planted grassland – class 7), (ii) forest plantations (classes 8 – 12), (iii) water bodies and wetlands (classes 13 – 14), (iv) bare rock and soil (classes 15-17), (v) cultivated areas (classes 23 – 29), (vi) urban areas (classes 30 – 46), and (vii) mines and quarries (classes 47 – 49). Similarly, non-natural land cover classes in the NLC 2013/2014 database include: (i) water bodies and wetlands (classes 1 – 3 and 37 – 38), (ii) cultivated areas (classes 10 – 31), (iii) forest plantations (classes 32 – 34), (iv) mines (classes 35, 36 and 39), (v) bare rock / soil and erosion classes (classes 40 – 41), and (vi) urban areas (classes 42 – 72). Modelling each of these classes is detailed below.

Improved grassland (planted grassland):
This land cover class, i.e. only defined for the NLC 2000 classification (Class 7), is modelled in a similar manner to the natural land cover classes, i.e. as detailed in Chapter 14, as an individual HRU, however, with its specified final *ACRU* land cover class (Table 12.1).

Forest plantations:
Forest plantations are represented by Classes 8 – 12 in the NLC 2000 database and include classes for different tree species (Pine, Eucalyptus, Acacia and other / mixed) as well as a clearfelled class. In the NLC 2013/2014 database (Classes 32 – 34) distinction between tree species is not made and classes are only defined as young, mature or clearfelled. In the CSM system developed all NLC forest plantation classes are represented by a single generalised final *ACRU* forestry land cover class (Table 12.1 and Table 13.1). Therefore, if more than one forestry class from the NLC 2000 or NLC 2013/2014 shapefiles/rasters is present in the catchment, these classes are lumped together and modelled using a single representative final *ACRU* land cover class. As mentioned above, the NLC 2000 classification distinguishes between tree species, however, the NLC 2013/2014 classification does not. Therefore, for consistency, it was decided to represent all forestry classes using a single general forestry class. If the total area of forest plantations makes up more than 5% and is one of the dominant land covers, a forest HRU must be included and explicitly modelled. The intermediate class (Humus depth 50 – 100 mm, trees of intermediate age), with fair / intermediate site prep, was selected as the default for the NLC 2000 and NLC 2013/2014 forest plantation classes (Table 12.1 and

Table 13.1), *i.e.* from the range of possible classes from the final *ACRU* land cover classification (Table 11.1). If more detailed information is available, the user may select a more representative land cover class from the final *ACRU* land cover classification (Table 11.1), however, the aforementioned class has been assigned as the default. This applies to all default classes assigned, i.e. if the user has site-specific information the default land cover class can be replaced with the most appropriate land cover class from the final *ACRU* land cover classification (Table 11.1).

The generalisation of modelling all forest plantation classes, *i.e.* as identified in the NLC 2000 or NLC 2013/2014 shapefiles/rasters, at the intermediate age is considered to be reasonable due to the following. Plantations are generally planted in blocks at different times, *i.e.* with the objective being to have a constant rotation where every year at least one block is ready for harvest, and is then replanted and will be harvested again once at full growth (Schulze, 2013). Therefore, at any time there is generally a fair mix of trees of different ages (from newly panted, to fully grown), with an additional clearfelled area (Schulze, 2013). Therefore, it is considered reasonable to take the average, *i.e.* the intermediate growth stage, as being representative of the entire plantation area, and lumping any clearfelled areas with the other forestry classes, *i.e.* since clearfelling is part of the plantation management (Schulze, 2013).

Dryland cultivated areas:

In the NLC 2000 and NLC 2013/2014 classification, cultivated areas can be either dryland or irrigated (i.e. Pivots – NLC 2013/2014, which refers to irrigation application using centre pivots). Irrigated areas are dealt with differently in *ACRU* and therefore these classes are special cases and are elaborated on further under the special cases section. Owing to the differences in the classification of cultivated areas in the NLC 2000 and NLC 2013/2014 databases, the modelling procedure for each database is split into two separate sections below.

(i) NLC 2000 (Classes 24, 25, 27 and 28):

- Class 24 – Cultivated, permanent, commercial, dryland is assumed to be pasture in fair condition (Table 12.1), since this is a common permanent commercial land cover crop used in crop rotations or for permanent grazing by livestock.
- Class 25 – Cultivated, permanent, commercial, sugarcane is assumed to be cultivated with the implementation of conservation structures (*e.g.* contours and terraces), with partial cover, *i.e.* there is some space between cultivated rows where the ground

surface is visible or exposed. This is considered a reasonable assumption for commercial sugarcane crops.

- Class 27 - Cultivated, temporary, commercial, dryland is assumed to be dryland maize / row crops if situated in the summer rainfall zones (eastern and central parts of the country) and wheat / small grain crops if situated in the winter and all year rainfall zones (western parts of the country), as depicted in Figure 3.3 (after Schulze, 2013). Since it is a commercial crop it is assumed to be planted following the contours of the land and generally in good condition (Table 12.1), with commercial practice aimed at optimising crop yield.

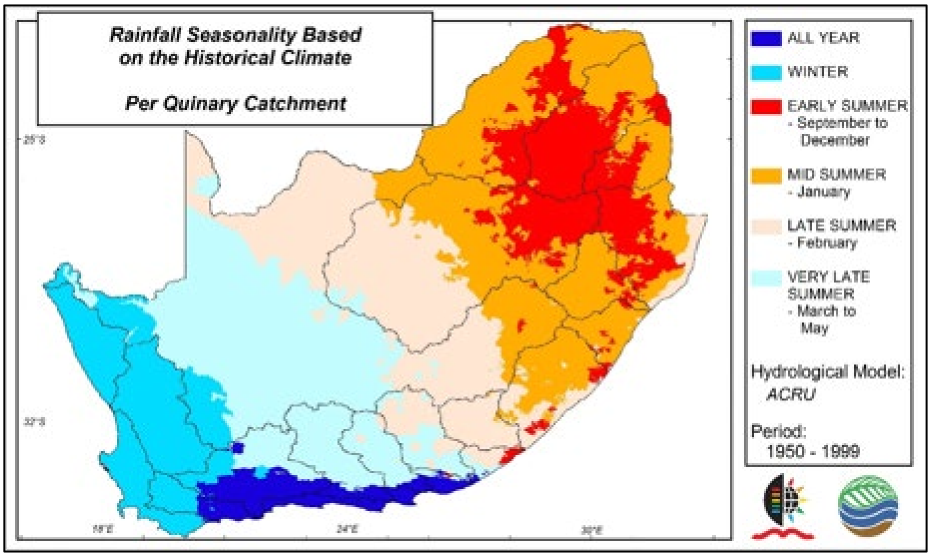

Figure 3.3 Rainfall seasonality (Schulze and Kunz, 2010)

- Class 28 - Cultivated, temporary, subsistence, dryland assumes the same conditions as for Class 27, however, since it is a subsistence crop it is assumed to be planted in straight rows up and down the slope or across the slope and generally in poor condition (Table 12.1), i.e. since less capital is available to perform the necessary steps needed to ensure optimal growth and maximise yields. These default assigned land cover classes are generalised best estimates, based on reasonable assumptions, however, where more detailed land cover information is available it should be used to assign the most appropriate land cover classes based on the actual verified land cover class, management practice, and hydrological condition identified.

- If any of these land cover classes are identified as one of the most dominant land cover classes, they are modelled in a similar manner to the natural land cover classes as individual HRUs, however, with their specified *ACRU* land cover classes (Table 12.1).

(ii) NLC 2013/2014 (Classes 10 – 12, 16 – 25 and 28 – 31):

- Classes 10 and 11 - Cultivated commercial fields (high yield) and (med yield), respectively, are assumed to be dryland maize / row crops if situated in the summer rainfall zones (eastern and central parts of the country) and wheat / small grain crops if situated in the winter and all year rainfall zones (western parts of the country), as depicted in Figure 3.3 (after Schulze, 2013). Since it is a commercial crop it is assumed to be planted following the contours of the land and generally in good condition (Table 13.1), with commercial practice aimed at optimising crop yield.
- Class 12 – Cultivated commercial fields (low yield) is assumed to be pasture in fair condition (Table 13.1), since this is a common permanent commercial land cover crop used in crop rotations or for permanent grazing by livestock.
- The default land cover classes assigned to the high, medium and low yield classes described above are based on the descriptions of these classes as defined by GEOTERRAIMAGE (2015). GEOTERRAIMAGE (2015), define high, medium and low yield land cover classes based on seasonal Normalised Difference Vegetation Index (NDVI) maximum and standard deviation ranges, which can be used as qualitative indicator levels of cultivation activity, crop rotations and / or productivity, with "low" representing areas of low maximum biomass growth and least seasonal variation; and "high" representing areas of high maximum biomass growth and greatest seasonal variation. Therefore, since maize and wheat are seasonal crops it was considered most appropriate to assign these classes to the high and medium yield classes, and since pasture is an all year crop with less seasonal variation in NDVI, it was considered most appropriate to assigned this class to the low yield class.
- The description of high, medium and low yield classes applies to all subsequent cultivated classes described in this section.
- Classes 16 to 21 – Cultivated orchards and vines (high, med and low yield) are all assumed to be orchards, i.e. winter rainfall region, understory of crop cover (Table 13.1). The final *ACRU* land cover classification (Table 11.1), adopted from the original SCS-SA classification, contains only this single land cover class for orchards.

Consequently, this is currently the most representative class available to represent all of the NLC 2013/2014 orchard and vine classes and was hence selected as the default.

- Class 22 – Cultivated permanent pineapple is assumed to be represented best by the garden crop land cover class (Table 13.1). Since this is defined as a commercial crop (GEOTERRAIMAGE, 2015), it is assumed to be in good condition.
- Classes 23 and 24 - Cultivated subsistence (high yield) and (med yield), respectively, are assumed to be dryland maize / row crops if situated in the summer rainfall zones (eastern and central parts of the country) and wheat / small grain crops if situated in the winter and all year rainfall zones (western parts of the country), as depicted in Figure 3.3 (after Schulze, 2013). Since it is a subsistence crop it is assumed to be planted in straight rows up and down the slope or across the slope and generally in poor condition (Table 13.1).
- Class 25 – Cultivated subsistence (low yield) is assumed to be pasture in poor condition (Table 13.1).
- Classes 28 to 31 – Cultivated cane commercial and emerging are all assigned a final *ACRU* land cover class (Table 11.1) of sugarcane with conservation structures and partial cover (Table 13.1). The cropped and fallow classes are lumped together and modelled using this single default assigned land cover class, since combinations of both cropped and fallow fields are likely to occur at any particular point in time. The user, however, has the option to select the most appropriate class from the final *ACRU* land cover classification (Table 11.1) based on site-specific information.

#### 3.3.2.3 Modelling special case land cover classes

Special case land cover classes (HRUs) and / or model configurations are required for the following special cases: irrigated areas; land cover classes with impervious areas (*i.e.* urban areas; bare rock / soil; mines / quarries); and water bodies. Each of these special cases must be modelled as described below, *i.e.* if they make up one of the most dominant land cover classes within the catchment or are considered to have a significant influence on the hydrology, *i.e.* with respect to water bodies.

Irrigated cultivated areas:

If irrigated agricultural land cover classes are one of the most dominant land cover classes identified, they are modelled as special case HRUs, called irrigated areas in *ACRU*, with their specified *ACRU* land cover classes. Due to the differences in the classification of cultivated irrigated areas in the NLC 2000 and NLC 2013/2014 databases, the modelling procedure for each database is split into two separate sections below.

(i) NLC 2000 (Classes 23, 26, and 29):

- Class 23 – Cultivated, permanent, commercial, irrigated is assumed to be irrigated pasture in good condition (Table 12.1), since this is a common permanent commercial land cover crop, usually well irrigated (*e.g.* centre pivots, or other large scale commercial irrigation systems), and used for permanent grazing by livestock, with blocks used in rotations.
- Class 26 - Cultivated, temporary, commercial, irrigated is assumed to be irrigated maize / row crops if situated in the summer rainfall zones and wheat / small grain crops if situated in the winter and all year rainfall zones (Figure 3.3). Since it is a commercial crop it is assumed to be planted following the contours of the land and generally in good condition (Table 12.1), with commercial practice aimed at optimising crop yield.
- Class 29 - Cultivated, temporary, subsistence, irrigated assumes the same conditions as for Class 26, however, since it is a subsistence crop it is assumed to be planted in straight rows up and down the slope or across the slope (Table 12.1). These default assigned land cover classes are generalised best estimates, based on reasonable assumptions, however, where more detailed land cover information is available it should be used to assign the most appropriate land cover classes based on the actual verified land cover class, management practice, and hydrological condition identified.

(ii) NLC 2013/2014 (Classes 13 – 15 and 26 – 27):

- Classes 13 and 14 - Cultivated commercial pivots (high yield) and (med yield), respectively, are assumed to be irrigated maize / row crops if situated in the summer rainfall zones and wheat / small grain crops if situated in the winter and all year rainfall zones (Figure 3.3). Since it is a commercial crop it is assumed to be planted following the contours of the land and generally in good condition (Table 13.1).

- Class 15 – Cultivated commercial pivots (low yield) is assumed to be irrigated pasture in good condition (Table 13.1), since this is a common irrigated permanent commercial land cover crop used in crop rotations or for permanent grazing by livestock.
- Classes 26 and 27 – Cultivated cane pivot (crop and fallow) are both assigned a final *ACRU* land cover class (Table 11.1) of sugarcane with conservation structures and partial cover (Table 13.1) with irrigation applied.

The following additional default rules for simulating irrigated areas, as suggested by Schulze (2013) have been defined. Irrigation must be sourced from a dam if there is one situated within the catchment or a river channel. In either case, either a dam or a river channel needs to be added to the model structure, and represented in one of two ways:

Configuration 1 – The irrigated area is, and all other HRUs for that fact are, assumed to be situated above the water source (dam / river), with the assumption that return flows re-enter the water source and the water source is situated at the outlet of the catchment (Schulze, 2013). For the CSM system developed this is the default configuration to apply when adding an irrigated area HRU.

Configuration 2 – Identical to configuration 1 if irrigation is from a river. If, however, irrigation is from a dam another, hydrologically more correct, option is to represent the actual location of the dam/s in the catchment. Therefore, the actual area of the catchment that drains to the dam/s needs to be determined, *e.g.* from NLC 2000 or NLC 2013/2014 maps, and this area needs to be represented by a separate HRU or HRUs. The streamflow relationships within *ACRU* then need to be configured so that only streamflow from this specific area drains to the dam and therefore determines the outflow (overflow) from the dam. This water is then transported further downstream to the catchment outlet via a river channel, and water is added to the channel from the other HRUs identified in the catchment located below the dam. Therefore, based on the actual location of the irrigated area and the dam/s, the irrigated area may be above or below the dam. This configuration, although not suggested for use in the CSM system developed, is worth mentioning and may be incorporated into the CSM system in the future, i.e. with comparison of the performance of each of the two configurations.

In addition to the default irrigation configuration (Configuration 1) defined, there are several options in the *ACRU* model regarding how or when irrigation is applied (Schulze, 1995). Schulze (2013) recommends that irrigation scheduling Option 1 (refill to Drained Upper Limit (DUL), initiated at a set percentage of the Plant Available Water (PAW) content, defaulted to 50% of PAW, must be used if irrigation is sourced from a dam, and suggests default general loss fractions, and rules when applying this option for irrigated areas. If, however, irrigation is sourced from a river, Schulze (2013) recommends that irrigation Option 2 (fixed cycle fixed amount) must be used, i.e. with the rules and defaults defined for this option. These default irrigation options, as suggested by Schulze (2013), were retained and selected for use with the CSM system developed. The modeller, however, is provided with all the irrigation options available in the *ACRU* model and may change the default based on more detailed, site-specific, information about the catchment being investigated.

Another possibility is to include an option for irrigation from an external source not within the catchment being investigated, *i.e.* "Large irrigation projects frequently obtain water from remote sources, often hundreds of kilometres from the point of irrigation water demand" (Schulze, 1995 *ACRU* Theory (AT) 18 - 2). This, however, is generally only applicable to significantly large catchments, currently the focus is on small catchments 0 – 100 km$^2$ where the water source is within the catchment.

<u>Impervious areas</u>:

The following imperious land cover classes are defined for the NLC 2000 and NLC 2013/2014 land cover databases.

(i) NLC 2000:

- Bare rock / soil (Classes 15 – 17), Urban areas (Classes 30 – 46) and Mines / quarries (Classes 47 – 49).

(ii) NLC 2013/2014:

- Mines (Classes 35, 36, 39), Erosion – donga (Class 40), Bare none vegetated (Class 41) and Urban areas (Classes 42 – 72).

All impervious areas identified within a catchment, as defined above for each of the NLC databases, are lumped into one special class or case. Each impervious land cover class also comprises of a pervious portion, *i.e.* 100% minus the sum of adjunct and disjunct impervious area percentages. Adjunct impervious areas are directly connected to drainage lines and stormwater drains and consequently contribute directly to streamflow. Disjunct impervious areas are not directly connected to the river and therefore stormflow from these areas flows onto surrounding pervious land cover classes and contributes to the water balance of these pervious areas. If these land cover classes, *e.g.* from the NLC 2000 or NLC 2013/2014 datasets, combined (or individually), make up one of the dominant land cover classes then this land cover class or combination of land cover classes is modelled as follows.

Firstly, both an adjunct and a disjunct area must be added to the model configuration, *i.e.* since most of the impervious land cover classes are made up of combinations of adjunct and disjunct areas (Table 11.1). If, however, the impervious land cover classes identified within the catchment only have an adjunct or only a disjunct area then only an adjunct or disjunct area must be added. The final adjunct and disjunct areas (km$^2$) are derived by summing up the adjunct and disjunct areas defined for each respective impervious land cover class.

A pervious land cover class is assigned to each impervious land cover class (Table 11.1). Two classes, either improved grassland (planted grassland) in fair condition or unimproved (natural) grassland in poor condition, have been assigned to each impervious land cover class, *e.g.* in terms of urban areas improved grassland (planted grassland) in fair condition is assigned to high income (formal) urban and sub-urban residential areas and unimproved (natural) grassland in poor condition to low income (informal) rural settlements. Therefore, if the combination of impervious land cover classes has pervious portions with both of the aforementioned land cover classes, two HRUs to represent each of these pervious portions needs to be added to the model structure. The areas (km$^2$) of these pervious HRUs are to be calculated for each impervious land cover class and similar pervious land cover classes added together to form a single HRU for each of the two pervious classes. If only one pervious class, e.g. grassland (planted grassland) in fair condition, is identified from the impervious classes within the catchment, then only one pervious HRU class is required.

Water bodies:

In the NLC 2000 database there are two classes for water bodies, Class 13 – water bodies and Class 14 – wetlands. In the NLC 2013/2014 database there are five classes for water bodies including permanent water bodies (Classes 2 and 38), seasonal water bodies (Classes 1 and 37), and wetlands (Class 3). As a default, seasonal water bodies (NLC 2013/2014) must not be modelled explicitly and must be assumed to be part of the most dominant land cover class, i.e. the baseline land cover class. Water bodies (NLC 2000) and permanent water bodies (NLC 2013/2014) must only be modelled explicitly if they are likely to significantly influence the hydrology of the catchment, or are considerably large. If a water body, e.g. a dam, makes up more than 5% of the total catchment area, it must be explicitly represented and modelled as detailed below, otherwise assumed to be part of the most dominant land cover class.

As described above for irrigated areas (Configuration 1), if a water body (dam) or more than one dam is identified within the catchment, the dams are combined and modelled as one large dam at the outlet of the catchment and all irrigation is taken from this dam (after Schulze, 2013).

Additional defaults and suggested values from Schulze (2013) are used when modelling dams, *e.g.* seepage, environmental flows, dead storage values, evaporation losses (i.e. for 4 different zones in South Africa, based on adjustment of Apan evaporation), and water transfers into and out of the dam, excluding irrigation, if these are to be considered.

Owing to the fact that wetlands generally cover very small areas in South Africa (Schulze, 2013), wetlands are assumed to be part of the most dominant land cover class and not modelled explicitly, unless the wetland makes up a substantial area of the catchment under consideration (more than 5%), in which case it must be modelled as a shallow dam (after Schulze, 2013).

## 3.4 Conclusions

This chapter has provided some background on previous developments towards a CSM approach for DFE in South Africa. Building on from these initial results, an improved comprehensive CSM system for DFE in South Africa, applicable to small catchments (up to 100 km$^2$), and using the *ACRU* model, has been developed. The system provides a consistent methodology to represent land management practices and hydrological conditions, which are currently not represented, or not adequately represented, in the *ACRU* model. In addition, in the current default implementation of the *ACRU* model, two parameters that significantly influence stormflow response (*QFRESP* and *SMDDEP*) are generally set to default values. The CSM system developed, now provides a consistent methodology to estimate these parameters based on physically measurable catchment characteristics, i.e. soils and land cover information. Several default input datasets, configurations, model options, and land cover and soils classifications, to apply the CSM system have been provided. This information is used in the following chapter to assess and compare the performance of the CSM system developed to that of the current default implementation of the *ACRU* model. The assessment and verification of the CSM system developed is performed for selected land cover classes where adequate observed data are available, i.e. in terms of rainfall and streamflow data. It is not possible to perform the assessments for all the land cover classes defined in this chapter owing to data limitations and the time required to acquire and validate the accuracy of the data. A comprehensive system, however, has been defined and is a good baseline from which to work and progress. The objectives of the chapters to follow are to identify if reasonable results are obtained for selected land cover classes, which builds confidence in the model and the CSM system developed and justifies further development and assessment of the approach for additional land cover classes. It should be noted, however, that the availability of observed data for specific land cover classes with specific combinations of soils information is limited in South Africa, and therefore verification of the system for certain land cover classes such as agricultural crops and urban areas may not be possible, particularly when trying to verify the hydrological responses from a single land cover and soil combination, i.e. as most catchments have a range of land cover classes occurring within the catchment. However, given the consistency in the configuration and parameterisation of the *ACRU* model outlined above, it is assumed that confidence gained from the verification of simulated hydrological responses for gauged catchments is transferred to application of the model for unverified land cover and soils combinations.

# 4. PERFORMANCE ASSESSMENT OF THE IMPROVED CONTINUOUS SIMULATION MODELLING SYSTEM DEVELOPED COMPARED TO THE CURRENT DEFAULT *ACRU* MODEL CONFIGURATION

This chapter assesses and compares the performance of the improved CSM system described in the previous chapter, to that of the current default implementation of the *ACRU* model.

## 4.1 Introduction

In the previous chapter an improved CSM system for DFE in South Africa was defined, including the structure of the system, how to implement the system and the default input information to use with the system, i.e. when site-specific information is not available. The system was developed in order to consistently and explicitly represent land management practices and hydrological conditions as represented in the SCS-SA model, which are not adequately represented in the current default implementation of the *ACRU* model. To achieve this, a land cover classification for use with the CSM system developed was required (Table 11.1). As described in the previous chapter, the land cover classification was adopted from the original SCS-SA land cover classification. However, some revisions were made to more adequately represent the NLC 2000 and NLC 2013/2014 land cover classes. The *CN*s from the revised SCS-SA classification were used to parameterise the *ACRU QFRESP* and *SMDDEP* parameters for each of the land cover and SCS-SA soil group combinations defined in the classification. In summary, in order to implement the CSM system developed, an estimate of the SCS-SA soil group for the catchment is required in addition to the land cover class. The general *ACRU* soil property inputs, e.g. topsoil and subsoil depths, permanent wilting point, field capacity, porosity and soil horizon response fractions, are determined based on the SCS-SA soil group, as summarised in Table 3.4 (Rowe, 2015).

Alternatively, in the current default implementation of the *ACRU* model (prior to the development of the CSM system referred to above), an estimate of the SCS-SA soil group for the catchment is not required and the general *ACRU* soil property inputs are obtained from a national soils map developed by Schulze and Horan (2008). In addition, *QFRESP* is simply set to a default value of 0.3 and *SMDDEP* is default to the depth of the topsoil, regardless of the land cover class or soil properties of the catchment.

The objectives of this chapter are to: (i) provide some background to the *ACRU* model and particularly the simulation of stormflow (surface and near-surface runoff), total streamflow (stormflow and baseflow), and peak discharge, and (ii) assess and compare the performance of the improved CSM system developed to that of the current default implementation of the *ACRU* model, for selected verification catchments. The comparison will confirm if the CSM system developed provides more reliable results compared to the current default implementation of the *ACRU* model and will highlight components of the system, or default *ACRU* model configuration, that require further development or refinement.

## 4.2 Streamflow and Peak Discharge Computation in the *ACRU* Model

In the *ACRU* model several algorithms and parameters are used to transform rainfall into total streamflow, i.e. both stormflow and baseflow. This includes partitioning rainfall into the various hydrological processes, such as interception, stormflow, soil water recharge, evapotranspiration and baseflow. It is not practical to describe all the details of each of these processes within this chapter, however, specific processes particularly relevant to this study that are needed to understand the methodology applied and results obtained, are summarised below. For further details on the information described below refer to Schulze (1995).

At the heart of the *ACRU* model is the SCS (1956) runoff equation, as represented in Equation 1.1 in Section 1.2 (Schulze, 1995), which is used to estimate stormflow ($Q$), referred to as *STORMF* in the *ACRU* model.

In summary, as depicted in Figure 1.2, once interception has been abstracted, the net daily precipitation ($P$), referred to as *RFL* in the *ACRU* model, is converted into *STORMF*, based on the soil water deficit ($S$) and the loss coefficient ($c$), referred to as the coefficient of initial abstraction (*COIAM*) in the *ACRU* model. The multi-layer soil water budgeting approach used in the *ACRU* model determines the value of $S$ on a day-by-day basis, which is calculated for a selected Critical Response Depth of the Soil (*SMDDEP*). The *STORMF* generated on a specific day is added to the stormflow store (*STORMF STORE*), which is partitioned into a Same Day

Response Fraction (*UQFLOW*), and a subsequent delayed stormflow response, i.e. by applying a Quick Flow Response Coefficient (*QFRESP*), which is a surrogate for interflow. The delayed stormflow response is retained in the *STORMF STORE*, to which the next day's *STORMF* is added, if any, which is then again partitioned based on the *QFRESP* coefficient. All rainfall that is not lost to interception or converted to *STORMF*, infiltrates into the topsoil. This rainfall adds to the soil water storage, from which evapotranspiration occurs. Dependent on the soil water content of the topsoil and subsoil horizons of the soil, water cascades through the soil profile under saturated and unsaturated conditions and contributes to the groundwater store, from which baseflow is generated and contributes to total streamflow.

In the current, publicly available, versions of the *ACRU* model, all the *STORMF* generated on the day is then used to estimate the peak discharge. The peak discharge calculation is derived from the SCS (1956), as represented in Equation 4.1 (Schulze, 1995), using an incremental triangular unit hydrograph approach to estimate the stormflow hydrograph and peak discharge.

$$\Delta q_p = 0.2083\left(\frac{A\,\Delta Q}{\frac{\Delta D}{2}+L}\right) \tag{4.1}$$

where

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

$A$ = catchment area [$km^2$],

$\Delta Q$ = incremental stormflow depth [mm],

$\Delta D$ = incremental duration of effective rainfall [hours], and

$L$ = catchment lag [hours].

In the standard *ACRU* model, incremental triangular unit hydrographs are only used if the hydrograph routing option is evoked. In this mode incremental triangular unit hydrographs are generated at fixed time intervals, for incremental stormflow depths determined based on the daily rainfall disaggregated into a hyetograph using one of four synthetic regionalised rainfall distributions (Weddepohl, 1988), and superimposed to provide a composite surface runoff hydrograph. The simulated baseflow from the model is then added to the ordinates of the surface runoff hydrograph, *i.e.* to provide a complete hydrograph (Schulze, 1995).

When the hydrograph routing option is not selected, which is generally the default option, a single triangular unit hydrograph is used to calculate stormflow peak discharge, and the effective storm duration ($\Delta D$) is assumed to be equal to the catchment's time of concentration ($T_c$), which is empirically related to lag time ($L$) through Equation 4.2 (Schulze, 1995).

$$L = 0.6\ (T_c) \tag{4.2}$$

Based on this assumption and combining Equations 4.1 and 4.2, Equation 4.1 simplifies to:

$$q_p = 0.2083 \left(\frac{A\,Q}{1.83\,L}\right) \tag{4.3}$$

Equation 4.3 is the default option in *ACRU* to calculate peak discharge and was used in this chapter to estimate the stormflow contribution to peak discharge. Further details regarding the baseflow contribution to peak discharge are provided later in this chapter.

It is evident from these equations that the simulated peak discharge is directly dependent on the simulated stormflow volume. Consequently, accurate estimates of daily stormflow volumes are central to accurately simulating daily peak discharges. In addition, an accurate estimate of the catchment lag time is important. In the *ACRU* model there are four options available to estimate catchment lag ($L$) namely: (i) time of concentration, (ii) summation of travel times along flow path reaches, (iii) the SCS lag equation, and (iv) the Schmidt-Schulze lag equation (Schulze, 1995). The Schmidt and Schulze (1984) lag equation (Equation 4.4) which was derived using data from research catchments was selected for the assessment of the CSM system developed, as recommended by Schulze (1995). Comparison of the performance of different lag equations is reported on in subsequent chapters on model/system sensitivity. The Schmidt and Schulze (1984) lag equation is expressed as:

$$L = \frac{A^{0.35}\ MAP^{1.1}}{41.67\ y^{0.3}\ \bar{\mathrm{I}}30^{0.87}} \tag{4.4}$$

where

$L$ = catchment lag [hours],

$A$ = catchment area [km$^2$],

$MAP$ = mean annual precipitation [mm],

$y$ = average catchment slope [%], and

$\bar{I}_{30}$ = 2-year return period 30-minute rainfall intensity [$mm.h^{-1}$].

### 4.3 Methodology

The following methodology was applied in this chapter:

(i) Eleven catchments, which included seven research catchments and four Department of Water and Sanitation (DWS) gauged catchments (Figure 4.1), with quality controlled observed rainfall and streamflow data, were selected to assess and compare the performance of the improved CSM system developed, as described in Chapter 3, to that of the current default implementation of the *ACRU* model. Obtaining observed data of suitable quality for this study was a major challenge as detailed in Section 4.4.2.

(ii) Catchment characteristics such as soils and land cover information were identified for each verification catchment, and were used to parameterise the *ACRU* model in applying both the current default implementation of the *ACRU* model and the improved CSM system developed, as detailed in Section 4.4.1.

(iii) After setting up the *ACRU* model with all the required inputs for both scenarios, daily streamflow and peak discharge were simulated at all verification catchments and for both scenarios.

(iv) Graphical comparisons of the simulated versus observed daily streamflow and peak discharge results were performed, and summary statistics calculated including: least square linear regression analysis to determine best fit regressions for the simulated versus observed results, along with the coefficient of determination ($R^2$). In addition, the Nash–Sutcliffe Efficiency (NSE) statistic of the observed versus simulated daily streamflow and peak discharge values was calculated.

(v) The Annual Maximum Series (AMS) was then extracted from both the daily observed and simulated streamflow volumes and peak discharges. The Generalised Extreme Value (GEV) distribution, as recommended for use in South Africa by Görgens (2007), was fitted using L-moments (Hosking and Wallis, 1997) to the AMS of the observed and simulated flows to compare how well the model simulated the design flood events, *i.e.* for the 2, 5, 10, 20, 50 and 100 year return periods. For comparison, and to summarise the differences between the observed and simulated design values across all return periods, both the Mean Relative Error (MRE), Equation 4.5, and the Mean Absolute Relative Error (MARE), Equation 4.6, were used. The MRE indicates general over or under-simulation, while the MARE indicates the total error, which compliments the MRE and indicates if there is consistent under or over-simulation or a combination of the two.

$$MRE = \frac{1}{n}\sum_{i=1}^{n}\frac{Sim_i - Obs_i}{Obs_i} \tag{4.5}$$

$$MARE = \frac{1}{n}\sum_{i=1}^{n}\frac{|Sim_i - Obs_i|}{Obs_i} \tag{4.6}$$

where

$MRE$ = mean relative error (0 - ∞; objective is to minimise MRE),

$MARE$ = mean absolute relative error (0 - ∞; objective is to minimise MARE),

$Sim_i$ = simulated design value, from GEV distribution, for return period i [mm or $m^3.s^{-1}$],

$Obs_i$ = observed design value, from GEV distribution, for return period i [mm or $m^3.s^{-1}$], and

$n$ = number of return periods.

## 4.4 Catchments Used for Verification

The 11 catchments selected to verify and compare the performance of the CSM system developed to that of the default implementation of the *ACRU* model are located as shown in Figure 4.1. These include seven research catchments monitored by the Council for Scientific and Industrial Research (CSIR), Forestek, and the University of KwaZulu-Natal (UKZN), and four DWS gauged catchments. DWS gauged catchments are indicated with blue dots in Figure 4.1 and research catchments with red dots. There are two catchments located at both the Cedara and DeHoek / Ntabamhlope research catchment sites (Figure 4.1). The catchment areas ranged from 0.26 to 77.16 $km^2$ as summarised in Table 4.1.

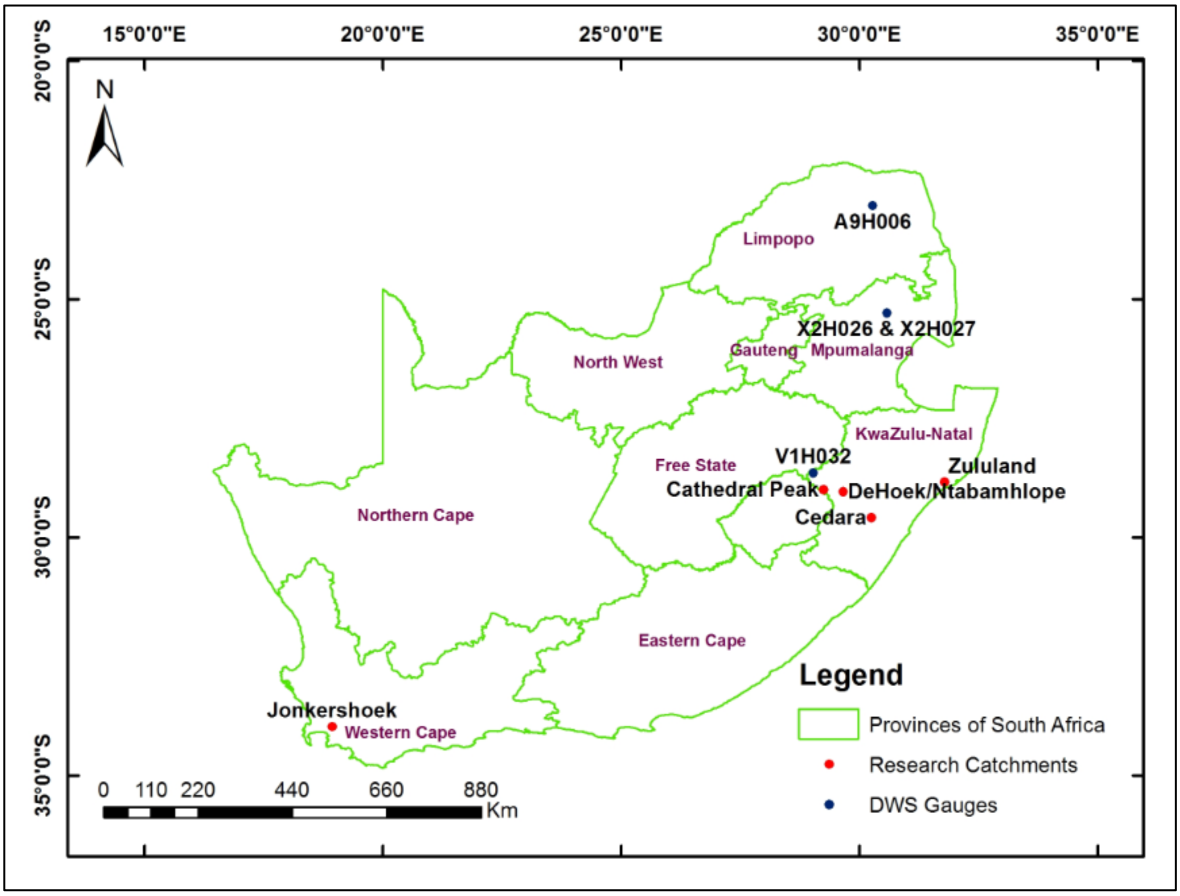

Figure 4.1 Location map of catchments used in verification studies

### 4.4.1 General climatic and physiographical characteristics

The Mean Annual Precipitation (MAP) values for the catchments were obtained using the national rainfall database and Geographic Information System (GIS) grids, developed by Lynch (2003). All GIS analyses were performed using the ArcGIS 10.4 software (ESRI, 2016). Catchment areas were obtained from publications for the research catchments (Smithers and Schulze, 1994a; Smithers and Schulze, 1994b; Scott *et al.*, 2000; Gush *et al.*, 2002; Royappen, 2002; Royappen *et al.*, 2002; Lorentz and van Zyl, 2003), and from the DWS website for gauging weirs monitored by DWS. Verification of all catchment areas was performed via the following steps: (i) Google Earth was used to identify and confirm the exact location of the streamflow gauging weirs, (ii) ArcGIS 10.4 was used to delineate the catchments, i.e. using the co-ordinates of the verified gauge locations and 1:50 000 topographical map sheets, available from the CWRR national GIS database obtained from the Chief Directorate of National Geo-spatial Information (CDNGI, 2013), formerly the Chief Directorate of Surveys and Mapping (CDSM), (iii) once the catchments had been delineated the areas were calculated using the

Calculate Geometry function in ArcGIS 10.4, (iv) these calculated areas were compared to those obtained from the sources listed above, and (v) corrections made if required, i.e. to the areas provided from the aforementioned sources. Similar to the MAP, the mean catchment altitude and slope was calculated in ArcGIS 10.4 using a 20 m Digital Elevation Model (DEM) available from the CWRR national database, also sourced from the CDNGI (2013). In addition to MAP, catchment areas, and mean catchment altitude, specific information about land cover and soils, as summarised in Table 4.1, was obtained from the literature (Smithers and Schulze, 1994a; Smithers and Schulze, 1994b; Scott *et al.*, 2000; Gush *et al.*, 2002; Royappen, 2002; Royappen *et al.*, 2002; Lorentz and van Zyl, 2003). This is the most accurate and detailed information available for the research catchments at the time of data collection and was used in preference to the default land cover (ARC and CSIR, 2005; DEA and GTI, 2015) and soils maps (Schulze, 2012), suggested for use with the CSM system developed (Chapter 3). DWS Gauges X2H026 and X2H027 fall within the Mokobulaan research catchment area and catchment X2H026 was one of the catchments used by Royappen (2002) and Royappen *et al.* (2002) for improved parameter estimation in streamflow predictions using the *ACRU* model. For the remaining two DWS gauges (A9H006 and V1H032) detailed information was not available and therefore the default land cover information from the NLC 2000 map was used, and the SCS-SA soils groups were obtained from the national SCS-SA soil group map developed by Schulze (2012), i.e. the recommended default information to use with the CSM system developed. In addition, in the absence of detailed land cover information for X2H027, the NLC 2000 information was also used for this catchment. However, the soils information was the same as that obtained for X2H026, i.e. from the literature describing the Mokobulaan area.

As alluded to in Section 4.2, Weddepohl (1988) delineated South Africa into four rainfall intensity distribution regions, and developed synthetic distributions of daily rainfall for each region. Region 1, with a Type 1 rainfall distribution, has the lowest rainfall intensity with rainfall more uniformly distributed throughout the day, while Region 4, with a Type 4 rainfall distribution, has the highest rainfall intensity with the majority of the daily rainfall falling within an hour (Weddepohl, 1988; Schulze, 1995). Using a map of the rainfall intensity distribution regions for South Africa obtained from Schulze *et al.* (2004), the rainfall intensity region for each catchment was identified. This was required to calculate $\bar{I}_{30}$, i.e. the 2-year return period 30-minute rainfall intensity, as needed to estimate the lag time using the Schmidt and Schulze (1984) lag equation (Equation 4.4). In order to calculate $\bar{I}_{30}$ an estimate of the 2-year return period maximum 1-day rainfall is multiplied by a multiplication factor defined for each region, available from Schulze (1995). A map of expected 1-day maximum rainfall values for South Africa, i.e. for the 2-year return period, is also available from Schulze (1995). This map can be used with the multiplication factors to calculate $\bar{I}_{30}$, however, the mapped values are very generalised. Consequently, the 2-year return period maximum 1-day rainfall was calculated from the daily rainfall record used to model each catchment, by extracting the AMS, fitting the GEV distribution with L-moments (Hosking and Wallis, 1997), and extracting the 2-year return period maximum 1-day rainfall from the distribution. The lag time was then calculated using Equation 4.4.

All the information summarised in Table 4.1 is required to apply the CSM system developed. Much of the information in Table 4.1 is also required to apply the current default implementation of the *ACRU* model, however, excluding the revised SCS-SA land cover class and the SCS-SA soil group. The *ACRU* land cover class assigned to the revised SCS-SA land cover class, i.e. for application in the CSM system developed, is also applicable to the current default implementation of the *ACRU* model. In the current default implementation of the *ACRU* model, however, the *QFRESP* (Table 4.1) and *SMDDEP* (Table 4.1) parameters are not determined based on the SCS-SA *CN*s, as performed for the CSM system developed. Instead, these parameters are set to default values. *QFRESP* is set at 0.3 for all catchments and *SMDDEP* is default to the depth of the topsoil. In addition, in the current default implementation of the *ACRU* model, the soil parameters required as input to the *ACRU* model are obtained from a national soils map developed by Schulze and Horan (2008). The soil parameter values obtained from this map for each of the verification catchments, required to apply the current default implementation of the *ACRU* model, are provided in Table 4.2. When applying the CSM system developed, these soil parameters are obtained from Table 3.4 based on the SCS-SA soil group as defined in the CSM system developed.

Table 4.1 Climatic and physiographical characteristics of the selected verification catchments required to apply the CSM system developed

| **Catchment** | **Area (km$^2$)** | **MAP (mm)** | **Mean Altitude (m)** | **Revised SCS-SA Land Cover Class** | **Treatment (Class) Type** | **Hydrological Condition** | ***ACRU* Land Cover Class Assigned to Revised SCS-SA Class (COMPOVEG Number / Source)** | **Mean Slope (%)** | **SCS-SA Soil Group** | ***CN*** | ***QFRESP*** | ***SMDDEP*** | **Rainfall Intensity Region** | **$\bar{I}30$ (mm/h)** | **Schmidt-Schulze Lag (h)** |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Cedara (U2H020)** | 0.26 | 1093 | 1106 | Unimproved (Natural) Grassland | 2 = in fair condition | Fair | UNIMPROVED GRASSLAND (5060103) | 11.00 | A/B | 61 | 0.59 | 0.25 | 3 | 49.52 | 0.54 |
| **DeHoek / Ntabamhlope (V7H003)** | 0.52 | 870 | 1497 | Unimproved (Natural) Grassland | 2 = in fair condition | Fair | UNIMPROVED GRASSLAND (5060103) | 14.60 | B/C | 75 | 0.91 | 0.25 | 3 | 51.49 | 0.47 |
| **Jonkershoek - Lambrechtsbos B (G2H010)** | 0.73 | 1074 | 517 | Forests & Plantations | Humus depth > 100mm | loose or friable / Site prep pitting | FOREST PLANTATIONS GENERAL (Schulze, 2013) | 36.39 | A/B | 33 | 0.3 | 0.45 | 2 | 39.54 | 0.64 |
| **Cathedral Peak IV (V1H005)** | 0.98 | 1264 | 2011 | Unimproved (Natural) Grassland | 3 = in good condition | Good | UNIMPROVED GRASSLAND (5060103) | 32.70 | A/B | 51 | 0.37 | 0.25 | 4 | 81.89 | 0.47 |
| **DeHoek / Ntabamhlope (V1H015)** | 1.04 | 943 | 1512 | Unimproved (Natural) Grassland | 3 = in good condition | Good | UNIMPROVED GRASSLAND (5060103) | 17.00 | B | 61 | 0.59 | 0.25 | 3 | 56.58 | 0.58 |
| **Cedara (U2H018)** | 1.31 | 946 | 1269 | Forests & Plantations | Humus depth > 100mm | loose or friable / Site prep pitting | FOREST PLANTATIONS GENERAL (Schulze, 2013) | 23.30 | B | 47 | 0.3 | 0.26 | 3 | 47.70 | 0.67 |
| **Zululand (W1H016)** | 3.30 | 1121 | 260 | Unimproved (Natural) Grassland | 3 = in good condition | Good | UNIMPROVED GRASSLAND (5060103) | 13.20 | B | 61 | 0.59 | 0.25 | 1 | 34.68 | 1.74 |
| **X2H026** | 13.82 | 978 | 1450 | Forests & Plantations (24%) | Humus depth 50 - 100mm | Fair/Intermediate site prep | FOREST PLANTATIONS GENERAL (Schulze, 2013) | 30.78 | A/B | 51 | 0.37 | 0.25 | 3 | 64.68 | 1.11 |
| | | | | Unimproved (Natural) Grassland (76%) | 3 = in good condition | Good | UNIMPROVED GRASSLAND (5060103) | | | | | | | | |
| **A9H006** | 16.00 | 1708 | 1055 | Forests & Plantations | Humus depth > 100mm | loose or friable / Site prep pitting | FOREST/NATURAL FOREST (5020101) | 32.34 | B/C | 52 | 0.39 | 0.25 | 2 | 63.76 | 2.16 |
| **V1H032** | 67.80 | 982 | 1571 | Unimproved (Natural) Grassland | 3 = in good condition | Good | UNIMPROVED GRASSLAND (5060103) | 26.50 | C | 74 | 0.89 | 0.25 | 3 | 79.55 | 1.71 |
| **X2H027** | 77.16 | 1026 | 1546 | Forests & Plantations (87%) | Humus depth 50 - 100mm | Fair/Intermediate site prep | FOREST PLANTATIONS GENERAL (Schulze, 2013) | 30.10 | A/B | 51 | 0.37 | 0.25 | 3 | 64.68 | 2.16 |
| | | | | Unimproved (Natural) Grassland (13%) | 3 = in good condition | Good | UNIMPROVED GRASSLAND (5060103) | | | | | | | | |

Table 4.2 *ACRU* soils input information obtained for each verification catchment from the national soils map developed by Schulze and Horan (2008)

| Catchments | Area (km$^2$) | DEPAHO (m) | WP1 (m.m$^{-1}$) | FC1 (m.m$^{-1}$) | PO1 (m.m$^{-1}$) | ABRESP/ BFRESP | DEPBHO (m) | WP2 (m.m$^{-1}$) | FC2 (m.m$^{-1}$) | PO2 (m.m$^{-1}$) |
|---|---|---|---|---|---|---|---|---|---|---|
| **Cedara (U2H020)** | 0.26 | 0.30 | 0.172 | 0.275 | 0.406 | 0.37 | 0.67 | 0.217 | 0.333 | 0.427 |
| **DeHoek / Ntabamhlope (V7H003)** | 0.52 | 0.30 | 0.150 | 0.240 | 0.422 | 0.42 | 0.63 | 0.208 | 0.292 | 0.413 |
| **Jonkershoek - Lambrechtsbos B (G2H010)** | 0.73 | 0.26 | 0.115 | 0.201 | 0.445 | 0.46 | 0.12 | 0.121 | 0.211 | 0.443 |
| **Cathedral Peak IV (V1H005)** | 0.98 | 0.30 | 0.134 | 0.224 | 0.439 | 0.39 | 0.55 | 0.156 | 0.248 | 0.410 |
| **DeHoek / Ntabamhlope (V1H015)** | 1.04 | 0.30 | 0.137 | 0.223 | 0.433 | 0.44 | 0.72 | 0.197 | 0.268 | 0.406 |
| **Cedara (U2H018)** | 1.31 | 0.30 | 0.170 | 0.270 | 0.410 | 0.37 | 0.62 | 0.212 | 0.324 | 0.425 |
| **Zululand (W1H016)** | 3.30 | 0.30 | 0.120 | 0.212 | 0.462 | 0.36 | 0.12 | 0.106 | 0.205 | 0.439 |
| **X2H026** | 13.82 | 0.30 | 0.173 | 0.280 | 0.399 | 0.38 | 0.67 | 0.199 | 0.317 | 0.425 |
| **A9H006** | 16.00 | 0.30 | 0.169 | 0.277 | 0.404 | 0.38 | 0.85 | 0.212 | 0.338 | 0.431 |
| **V1H032** | 67.80 | 0.30 | 0.144 | 0.233 | 0.432 | 0.38 | 0.36 | 0.177 | 0.265 | 0.416 |
| **X2H027** | 77.16 | 0.30 | 0.174 | 0.282 | 0.398 | 0.37 | 0.60 | 0.196 | 0.314 | 0.425 |

### 4.4.2 Data availability, collection and processing

The most frustrating and time-consuming component of this study was collating and processing the observed data required to assess the CSM system developed. The data had to be requested and sourced from various different organisations and databases, as explained below and summarised in Table 4.3, with many cases requiring manual searching through old archives and data stored on CD-ROMs, with grateful acknowledgements to Mr Arthur Chapman and Professor Jeff Smithers for assisting with this. The data then needed to be processed and converted into a standard format to use as input into the *ACRU* model. In terms of streamflow data, for many of the research catchments, only the original primary water level data were available, so rating tables had to be obtained to convert the levels to discharges. The data then needed to be error checked and verified, with many errors not flagged and only identified and corrected through manual investigation. An example of some typical errors in daily rainfall data are highlighted in Table 4.4, using Cathedral Peak IV (V1H005) as an example. The example shows that on several occasions rainfall events which continue over consecutive days, i.e. as recorded from autographic raingauges within the catchment, are lumped together into a single day in the daily rainfall data.

Table 4.3 Source of data, record lengths and modelling periods for verification catchments

| **Catchments** | **Cedara (U2H020)** | **DeHoek / Ntabamhlope (V7H003)** | **Jonkershoek - Lambrechtsbos B (G2H010)** | **Cathedral Peak IV (V1H005)** | **DeHoek / Ntabamhlope (V1H015)** | **Cedara (U2H018)** | **Zululand (W1H016)** | **X2H026** | **A9H006** | **V1H032** | **X2H027** |
|---|---|---|---|---|---|---|---|---|---|---|---|
| **Data Source Streamflow** | CWRR | CWRR | CSIR (Mr A Chapman) and SAEON | CSIR (Mr A Chapman) | CWRR | CWRR | CWRR | DWS | DWS | DWS | DWS |
| **Record Length** | 1978 - 1995 | 1970 - 1995 | 1947 - 2006 | 1950 - 1992 | 1965 - 1993 | 1977 - 1995 | 1977 - 1986 | 1967 - 1991 | 1962 - 2018 | 1974 - 1993 | 1967 - 1991 |
| **Data Source and ID Daily Rainfall** | CWRR - C191 infilled using C201 aggregated to daily | CWRR - N18 infilled using n14 aggregated to daily | SAEON - 15A aggregated to daily | CWRR / CSIR - C4 | CWRR - N11 infilled using N18 aggregated to daily | CWRR - C182 infilled using C191 aggregated to daily | CWRR - 304470 infilled using 304530 aggregated to daily | CWRR (Lynch, 2003) - SAWS station 0555137 W | CWRR (Lynch, 2003) - SAWS station 0723513 W | CWRR (Lynch, 2003) - SAWS station 0298818 W | CWRR (Lynch, 2003) - SAWS station 0555137 W |
| **Period of Record** | 1977 - 1996 | 1977 - 1995 | 1940 - 2008 | 1949 - 1987 | 1977 - 1993 | 1977 - 1995 | 1976 - 1986 | 1950 - 1999 | 1965 - 1996 | 1950 - 1999 | 1950 - 1999 |
| **Data Source and ID Hourly Rainfall and (Verification / Infilling Station)** | CWRR - C191 infilled using Raingauge C201 | CWRR - N18 infilled using Raingauge N14 | SAEON - 15A (SAWS station 0021809 W) | SAEON - C4_CD (C4) | CWRR - N11 infilled using N18 | CWRR - C182 infilled using C191 | CWRR - 304470 infilled using 304530 | CWRR Mokobulaan Raingauge 3A | N/A | N/A | CWRR Mokobulaan Raingauge 3A |
| **Record Length hourly (Record Length Verification / Infilling Station)** | 1977 – 1996 (1977 - 1996) | 1977 – 1995 (1977 - 1996) | 1940-2008 (1950 - 1999) | 1972 – 1979 (1949 - 1987) | 1977 – 1993 (1977 - 1995) | 1977 – 1995 (1977 - 1996) | 1976 – 1986 (1976 - 1986) | 1957 - 1984 | - | - | 1957 - 1984 |
| **Data Source Daily Tmin & Tmax** | CWRR (Schulze and Maharaj, 2004) | | | | | | | | | | |
| **Record Length of Daily Tmin & Tmax** | 1950 - 1999 | | | | | | | | | | |
| **Modelling Period (Years)** | 1978 – 1995 (17) | 1977 – 1995 (18) | 1972 – 1994 (22) | 1949 – 1981 (32) | 1979 – 1993 (14) | 1977 – 1995 (18) | 1977 – 1986 (9) | 1967 – 1991 (24) | 1965 – 1979 (14) | 1974 – 1993 (19) | 1967 – 1991 (24) |
| **Notes on Selected Modelling Period** | Short periods of missing streamflow data in 1980, 1982, 1983, 1992 and 1993. | Large gap in observed streamflow record with no data for the period 1973 - 1976. | Afforested to 82% *Pinus radiata* in 1964, modelled from 1972 - 1994, i.e. when trees were well established and therefore more stable and consistent land cover conditions. | Daily rainfall data missing in 1982, 1983, 1986 and 1987 therefore only modelled up to 1981. | Large gap in observed streamflow record with no data for the period 1968 - 1978. | Short periods of missing streamflow data in 1983, 1992, 1993, 1994 and 1995. | Short period of missing streamflow data between 1982 - 1983. | Hourly rainfall data not used for this chapter. | Dam built in catchment in approximately 1980 therefore only modelled to 1979. | Single driver rainfall station used, no other reliable rainfall stations considerably close to the catchment. | Hourly rainfall data not used for this chapter. Single driver rainfall station used (same as that used for X2H026). |

* CWRR - Centre for Water Resources Research; CSIR - Council for Scientific and Industrial Research; DWS - Department of Water and Sanitation; SAEON - South African Environmental Observation Network; SAWS - South African Weather Service

Table 4.4 Errors identified in the daily rainfall record for the Cathedral Peak IV Catchment

| Date | Daily Raingauge (mm) | Autographic Data (mm) |
|---|---|---|
| 1974/02/22 | 0.00 | 38.32 |
| 1974/02/23 | 81.00 | 47.14 |
| Total | 81.00 | 85.46 |
| 1976/03/03 | 22.00 | 60.08 |
| 1976/03/04 | 91.30 | 57.32 |
| Total | 113.30 | 117.40 |
| 1976/03/07 | 9.70 | 45.41 |
| 1976/03/08 | 73.40 | 44.82 |
| Total | 83.10 | 90.22 |

This may have occurred due to various reasons such as the inability to access the site on one of the days, staff away over weekends and general human error. These errors obviously have a significant influence on the simulated results, since rainfall is the primary driver of both streamflow volume and peak discharge response. In terms of short duration sub-daily rainfall records, the primary source of error is missing data due to instrument malfunction, which was often not flagged, i.e. with zero values in the record, but with the daily raingauges indicating significant rainfall. Occasionally, malfunction occurs over a certain period within the day, and therefore it is common to find daily totals from short duration raingauges being lower than those of the nearby daily rainfall stations (Smithers and Schulze, 2000). It is also important to note that there is a general lack of availability of observed sub-daily rainfall data, both spatially and in terms of record length, which limited the investigations that could be performed for certain catchments, i.e. where sub-daily rainfall data is required.

The errors in streamflow data include missing data records and over-topping of gauging weirs, i.e. rating table exceedance. Every effort was made to identify and correct such errors, however, this is a tedious task and can only be performed if adequate supplemental data is available, therefore inevitably there are potentially still some errors in the observed data, and which should be taken into account when assessing the simulated results. Significant time was spent on this critical step of data quality control, since accurate input data are essential when verifying a model and it is important to acknowledge that there is some uncertainty in the observed input and validation data. Furthermore, infilling and error correction, although an improvement, adds an additional level of uncertainty.

Obtaining consistent streamflow and rainfall data for long periods without any missing data was a significant challenge. In addition, there are periods with inconsistent rainfall and runoff data as a consequence of phasing issues, i.e. where rainfall and streamflow records are out of phase. For example, streamflow is recorded but with no rainfall on the same day, or rainfall is recorded for the preceding or subsequent day with no corresponding streamflow. Furthermore, in certain cases major land cover changes have occurred, such as for Catchment A9H006, where a dam was built in the catchment in approximately 1980. This was identified and verified using Google Earth images and therefore, for consistency, the modelling period was reduced to end in 1979. These challenges explain why only 11 catchments were used in the verification of the CSM system developed, and why in many cases relatively short modelling periods were used, i.e. from a design flood estimation perspective. Data issues, however, are and continue to be a major concern in South Africa with declines in monitoring networks highlighted by Wessels and Rooseboom (2009), Pitman (2011) and Pegram *et al.* (2016), and is a trend that is currently continuing. The sources of the data used are listed in Table 4.3. The record length available for each database is also provided, as well as the final modelling period, with explanation of why the final modelling period was selected.

In *ACRU* several methods have been developed and are available to estimate reference potential evaporation (Schulze, 1995). The method selected in this study was the Hargreaves and Samani (1985) equation which requires daily maximum and minimum temperature data only. This method was selected as a national database of high quality temperature data, developed by Schulze and Maharaj (2004), and is available from the CWRR.

The primary streamflow data, once formatted and error checked, as mentioned above, was processed as follows. A Python script was developed to read in the primary flow data, and calculate daily streamflow volumes using integration, i.e. calculated from 08:00 - 08:00 periods to be consistent with the daily rainfall data which are recorded for this period in South Africa. The programme simultaneously extracted the daily peak discharges for the same period from the primary flow data.

Where hourly rainfall data was used and aggregated to daily values (08:00 – 08:00), i.e. for use as the daily rainfall input into *ACRU*, the daily totals were compared to daily rainfall values from the closest daily rainfall station with high quality data. This included scatter plots as well as cumulative plots and visual inspections to identify possible errors or missing data in the hourly records. Where missing data were identified, rainfall was infilled using data from the selected daily station closest to the recording rainfall station. For several of the small research catchments, poor correlation between the daily total accumulated from the hourly rainfall station and the closest daily rainfall station, often several kilometers away, resulted in the use of other nearby hourly rainfall stations being used to infill a selected driver hourly rainfall station for each catchment, i.e. a single rainfall station with adequate data and most representative of the catchment rainfall. Since the hourly rainfall stations used to perform the infilling were very close to one another, a direct copy of the data from the nearby station selected for infilling was used to infill the data missing in the driver rainfall station selected. A regression analysis between the two stations was not used to adjust the infilled values since the regression only gives the general trend, whereas the values fluctuate around this trend on a day-to-day basis. Due to the general similarity in the observed data from these stations it was considered preferable to use the data directly from the station used for infilling as it gives the most realistic rainfall volume on each particular day, and eliminates any additional uncertainty associated with adjusting real values based on general trends.

## 4.5 Results and Discussion

A detailed example of the typical performance and results obtained from both the CSM system developed and the default *ACRU* model configuration is provided below for two of the verification catchments listed in Table 4.1, namely Cathedral Peak IV (V1H005) and DeHoek / Ntabamhlope (V1H015). These two catchments were selected since they are similar in size and have the same land cover, however, differ in hydrological response as a result of different soil properties. Cathedral Peak IV (V1H005) is characterised by an SCS-SA A/B soil group, while DeHoek / Ntabamhlope (V1H015) is characterised by an SCS-SA B soil group. In the CSM system developed, these catchments are consequently represented by different *QFRESP* parameter values (Table 4.1). In the current default implementation of the *ACRU* model, however, both catchments are represented by a fixed (default) *QFRESP* value of 0.3. In addition, when applying the CSM system, the soil parameters required as input to the *ACRU* model are those assigned to the SCS-SA soil group identified for the catchment (Table 3.4). In the default implementation of the *ACRU* model, however, the soil properties are obtained from the national soils map developed by Schulze and Horan (2008), as summarised in Table 4.2.

The detailed evaluation of these two catchments is followed by a summary of the performance across all verification catchments.

The NSE and least square linear regression analysis results for both catchments, applying both the CSM system developed in this study and the default *ACRU* model configuration, for both simulated and observed daily streamflow volumes and peak discharges, are provided in Figure 4.3 (Cathedral Peak IV - V1H005) and Figure 4.3 (DeHoek / Ntabamhlope - V1H015). Very similar results were obtained for the Cathedral Peak IV (V1H005) catchment, when applying both the CSM system and the default *ACRU* model configuration (Figure 4.3).

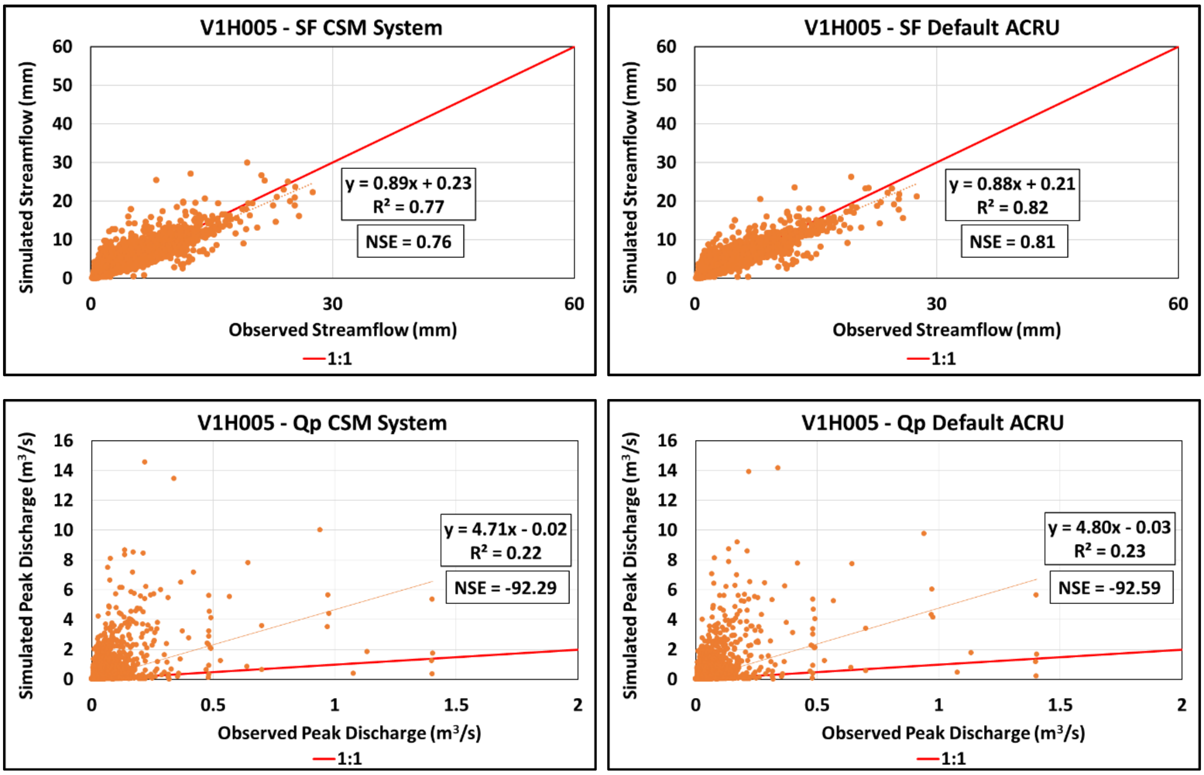

Figure 4.2 Simulated versus observed daily streamflow volumes (SF) and peak discharges (Qp) for the Cathedral Peak IV – V1H005 Catchment

This was expected since the *QFRESP* parameter values from both scenarios for this catchment are similar, i.e. 0.37 (CSM system) and 0.3 (default *ACRU* model configuration). In terms of daily streamflow volumes, good simulations were obtained for the Cathedral Peak IV (V1H005) catchment applying both the CSM system and the default *ACRU* model configuration. The results, however, were slightly better for the default *ACRU* model configuration, i.e. $R^2 = 0.82$ and NSE = 0.81 compared to the CSM system, i.e. $R^2 = 0.77$ and

NSE = 0.76. In both cases there is a slight under-simulation of the observed streamflow volumes, with a Regression Slope of 0.88 and 0.89 respectively. In terms of daily peak discharges, extremely poor simulations were obtained for the Cathedral Peak IV (V1H005) catchment applying both the CSM system and the default *ACRU* model configuration, i.e. with Regression Slopes greater than 4.70 (extreme over-simulation) and extremely low NSE values (less than -92.00). At the DeHoek / Ntabamhlope (V1H015) catchment the simulated streamflow volumes obtained are noticeably more under simulated when applying the default *ACRU* model configuration, i.e. Regression Slope = 0.56, compared to the CSM system, i.e. Regression Slope = 0.73. The $R^2$ and NSE values are however similar (Figure 4.3).

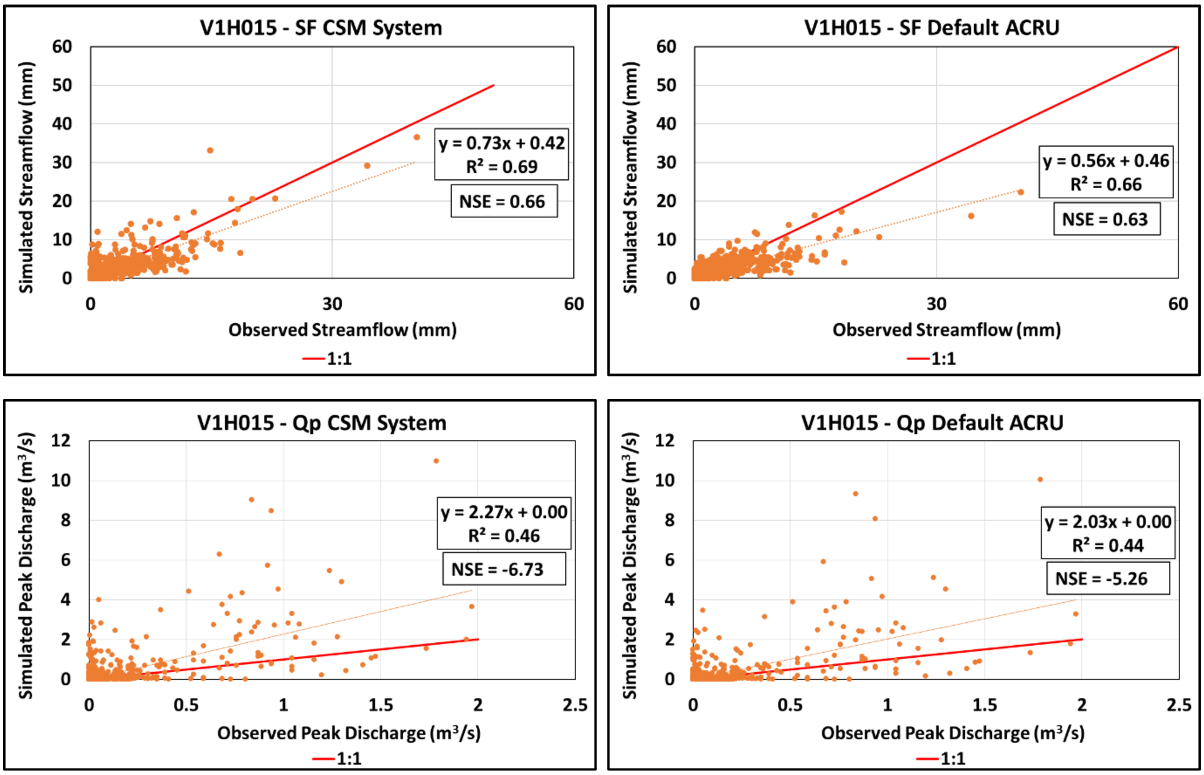

Figure 4.3 Simulated versus observed daily streamflow volumes (SF) and peak discharges (Qp) for the DeHoek / Ntabamhlope - V1H015 Catchment

This was expected since the *QFRESP* parameter value for this catchment when applying the CSM system is considerably higher (0.59) compared to that applied in the default *ACRU* model configuration (0.3). Owing to the higher *QFRESP* value applied in the CSM system, a greater fraction of the *STORMF* generated on each day with substantial rainfall is released on that day and therefore the daily simulated streamflow volumes are higher on the day of the rainfall event compared to those obtained from the default *ACRU* model configuration, i.e. where *QFRESP* is set at 0.3. The $R^2$ and NSE values remain similar since the correlation between observed and simulated streamflow does not change based on *QFRESP*, only the magnitude of the daily simulated streamflow response. The computation procedure is explained in more detail later in this chapter, using an example from an actual rainfall event. Therefore, in terms of the simulated streamflow volumes for this catchment, the CSM system provides better results. Similar to the results obtained for the Cathedral Peak IV (V1H005) catchment, the simulated peak discharges for the DeHoek / Ntabamhlope (V1H015) catchment are very poor, i.e. with Regression Slopes greater than 2.00 (considerable over-simulation) and low NSE values (less than -5.20). The results from the CSM system and the default *ACRU* model configuration for this catchment, in terms of simulated peak discharges are, however, similar. This was unexpected since the simulated streamflow volumes were substantially lower when applying the default *ACRU* model configuration, and since the simulated peak discharges are directly dependent on the simulated streamflow volumes (Equation 4.1 and 4.3), it was expected that the simulated peak discharges obtained from the default *ACRU* model configuration would be substantially lower. The design flood estimates for the two catchments, for both scenarios, are depicted in Figure 4.4 (Cathedral Peak IV - V1H005) and Figure 4.5 (DeHoek / Ntabamhlope - V1H015). The results support those presented above and confirm that reasonable daily streamflow volumes and design streamflow volumes are obtained when applying both the CSM system and the default *ACRU* model configuration. For the Cathedral Peak IV (V1H005) catchment the design streamflow volumes are very similar for both scenarios (Figure 4.4). For the DeHoek / Ntabamhlope (V1H015) catchment, however, the design streamflow volumes are under-simulated when applying the default *ACRU* model configuration, compared to those obtained when applying the CSM system (Figure 4.5). Therefore, overall, the CSM system provides superior daily streamflow volumes and design streamflow volumes for these two catchments. The results also confirm that the simulated daily peak discharges and design peak discharges are significantly over-simulated when applying both the CSM system and the default *ACRU* model configuration (Figure 4.4 and Figure 4.5). Of particular concern, however, was the fact that the design peak discharges for the DeHoek / Ntabamhlope (V1H015) catchment were very similar when applying both the CSM system and the default *ACRU* model configuration, despite substantially lower design streamflow volumes being obtained when applying the default *ACRU* model configuration (Figure 4.5).

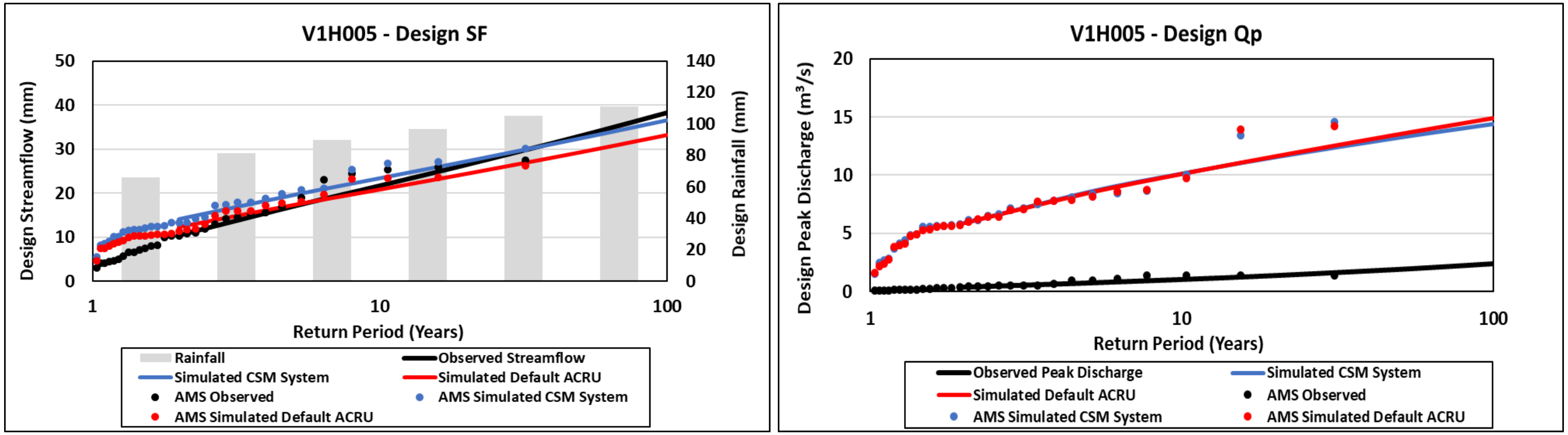

Figure 4.4 Design rainfall, design streamflow (SF) volumes and design peak discharges (Qp) for the Cathedral Peak IV (V1H005) Catchment

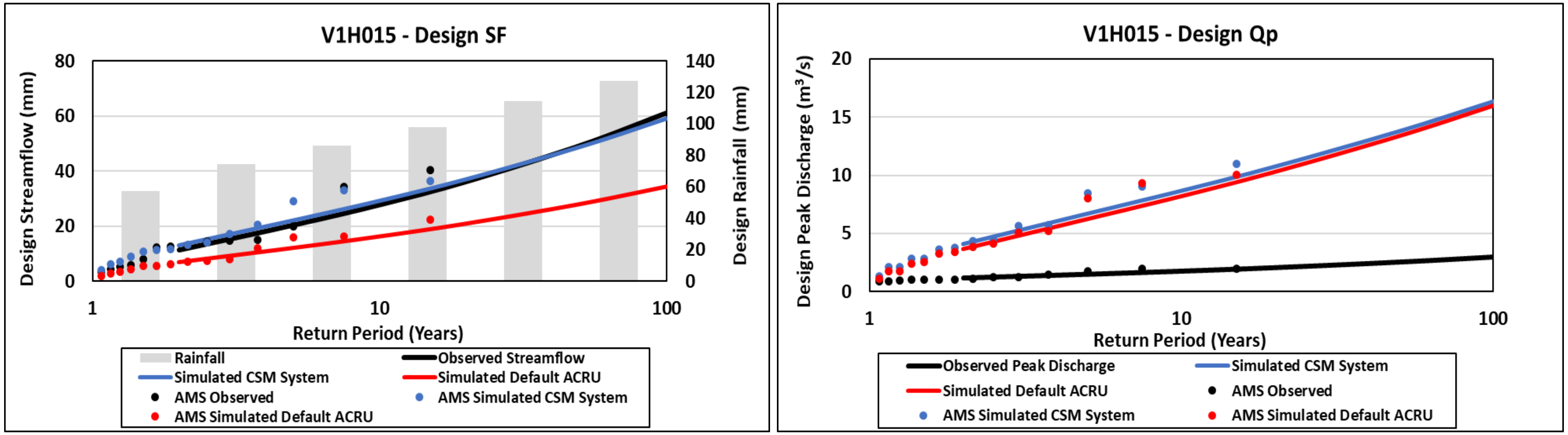

Figure 4.5 Design rainfall, design streamflow (SF) volumes and design peak discharges (Qp) for the DeHoek / Ntabamhlope (V1H015) Catchment

The poor Qp simulation results are best explained using an example. Table 4.5 provides an example of typical output information obtained from the *ACRU* model for Cathedral Peak IV, when applying the CSM system, to briefly explain the calculation of total simulated streamflow (*USFLOW*) and peak discharge (*QPEAK*) in the model. The observed streamflow and peak discharge for these days is also provided.

Table 4.5 Example output from the *ACRU* model simulated for Cathedral Peak IV, using the CSM system developed

| **DATE** | ***RFL*** **(mm)** | ***STORMF*** **(mm)** | ***STORMF STORE*** **(mm)** | ***UBFLOW*** **(mm)** | ***UQFLOW*** **(mm)** | ***USFLOW*** **(mm)** | ***QPEAK*** **($m^3$/s)** | **Observed Streamflow (mm)** | **Observed Peak Discharge ($m^3$/s)** |
|---|---|---|---|---|---|---|---|---|---|
| 1978/12/04 | 50.8 | 14.99 | 14.99 | 1.04 | 5.55 | 6.59 | 3.58 | 4.10 | 0.70 |
| 1978/12/05 | 1.7 | 0.00 | 9.44 | 1.30 | 3.49 | 4.79 | 0.01 | 2.23 | 0.04 |

The model firstly calculates the stormflow (*STORMF*) generated from the rainfall event on the day, if any, using Equation 1.1. As described in Section 4.2, Precipitation (*P*) is the rainfall for the day (*RFL*), minus interception. The *COIAM* (*c*) is a value defined for the month and the *S* value for the day is determined by the multi-layer soil water budgeting routines of the *ACRU* model, for the Critical Response Depth of the Soil (*SMDDEP*) selected. The *STORMF* for the day is then added to the *STORMF STORE*, and the total is multiplied by *QFRESP*, in this case 0.37, to yield the *UQFLOW* released from the *STORMF STORE* on the day. Therefore, for the 04/12/1978 *UQFLOW* = 5.55 mm, i.e. 14.99 x 0.37. The remaining stormflow from the *STORMF STORE* is retained in the *STORMF STORE*, which is carried over to the next day, i.e. 14.99 – 5.55 = 9.44 mm. The *STORMF* for the next day, i.e. if any, is then added to the *STORMF STORE*. In this case for the 05/12/1978 there is no *STORMF* generated on the day and therefore the *STORMF STORE* = 9.44 mm. The *STORMF STORE* for this day is again multiplied by *QFRESP*, to yield the *UQFLOW* for the day, i.e. 9.44 x 0.37 = 3.49 mm, and the procedure continues for the subsequent days. The simulated baseflow (*UBFLOW*) for each day is added to the *UQFLOW* for the day to yield the total simulated streamflow (*USFLOW*) for the day.

In terms of the peak discharge, the model currently uses all the *STORMF* generated for the rainfall event on the day in the stormflow peak discharge equation (Equation 4.3). This represents the stormflow (surface runoff) contribution to total peak discharge (*QPEAK*). Therefore, from the example above, for the 04/12/1978, the value of stormflow (*Q*) used in Equation 4.3 is 14.99 mm. This *STORMF* generated on the day, however, does not represent the actual fraction of stormflow that exits the catchment on the day, since this is partitioned into *UQFLOW* and a delayed *STORMF* response, conceptualised as interflow, as described above. This is therefore conceptually incorrect and results in inconsistent volumes between the *UQFLOW* volume released on the day, i.e. after applying *QFRESP* to the *STORMF STORE* (5.55 mm), and the volume of *STORMF* used to calculate the stormflow contribution to peak discharge (*QPEAK*) for the day (14.99 mm). The result is a significant over-simulation of *QPEAK* (3.58 m$^3$/s) compared to that observed (0.70 m$^3$/s), as reported in Table 4.5. In addition to the stormflow contribution to *QPEAK*, as calculated using Equation 4.3, *QPEAK* also comprises of a baseflow contribution. The baseflow contribution to peak discharge in the *ACRU* model is calculated by assuming a linear change in the rate of baseflow from one day to the next day, and is calculated as follows:

$$BFq_p = \frac{\frac{BF_i + BF_{(i-1)}}{2} \times A \times 1000}{24 \times 3600} \tag{4.7}$$

where

$BFq_p$ = baseflow contribution to total daily peak discharge [m$^3$.s$^{-1}$],

$BF_i$ = simulated baseflow for the current day [mm],

$BF_{(i-1)}$ = simulated baseflow for the previous day [mm], and

$A$ = catchment area [km$^2$].

The baseflow contribution to *QPEAK* is generally significantly lower than the stormflow contribution to *QPEAK* since *UBFLOW* is released very slowly from the baseflow store in the *ACRU* model, and this volume is uniformly distributed throughout the day, i.e. 24 hours, as indicated in Equation 4.7.

For clarity, using the example above (Table 4.5), Table 4.6 summarises how *QPEAK* in Table 4.5 was calculated, i.e. as simulated in the current versions of the *ACRU* model. For the 04/12/1978, *STORMF* for the current day, 14.99 mm in this case, is used with Equation 4.3 to estimate the contribution to *QPEAK* from stormflow, i.e. 3.56 m$^3$/s for this particular day (Column 5 - Table 4.6). The current ($BF_i$) and previous ($BF_{(i-1)}$) days *UBFLOW* is then used with Equation 4.7 to calculate the baseflow contribution to *QPEAK* (Column 6 - Table 4.6), 0.02 m$^3$/s in this case. Adding these two together *QPEAK* is obtained (Column 7 - Table 4.6), 3.58 m$^3$/s. The same procedure was applied for the results presented for the 05/12/1978.

Table 4.6 Peak discharge computation in the current versions of the *ACRU* model, as applied to the Cathedral Peak example events, when using the CSM system developed

| Column No. | 1 | 2 | 3 | 4 | 5 | 6 | 7 |
|---|---|---|---|---|---|---|---|
| DATE | *RFL* (mm) | *STORMF* (mm) | *UBFLOW* (mm) | *UQFLOW* (mm) | $q_p$ *STORMF* - Equation 4.4 ($m^3/s$) | $BFq_p$ - Equation 4.8 ($m^3/s$) | *QPEAK* current *ACRU* ($m^3/s$) |
| 1978/12/04 | 50.8 | 14.99 | 1.04 | 5.55 | 3.56 | 0.02 | 3.58 |
| 1978/12/05 | 1.7 | 0.00 | 1.30 | 3.49 | 0.00 | 0.01 | 0.01 |

To improve on the over-simulation of *QPEAK* and to correct the inconsistency between the *UQFLOW* volume released on a particular day, i.e. after applying *QFRESP* to the *STORMF STORE*, and the volume of *STORMF* used to calculate *QPEAK* for the day, the following revision was applied. Using the example above (Table 4.5), an additional output variable was defined and included as presented in Table 4.7, namely *UQFLOW ON THE DAY* (*UQFLOW OTD*).

Table 4.7 Updated example output from the *ACRU* model for Cathedral Peak IV, applying the CSM system developed

| **DATE** | ***RFL*** **(mm)** | ***STORMF*** **(mm)** | ***STORMF STORE*** **(mm)** | ***UBFLOW*** **(mm)** | ***UQFLOW*** **(mm)** | ***UQFLOW OTD*** **(mm)** | ***USFLOW*** **(mm)** | ***QPEAK*** **($m^3/s$)** | **Observed Streamflow (mm)** | **Observed Peak Discharge ($m^3/s$)** |
|---|---|---|---|---|---|---|---|---|---|---|
| 1978/12/04 | 50.8 | 14.99 | 14.99 | 1.04 | 5.55 | 5.55 | 6.59 | 3.58 | 4.10 | 0.70 |
| 1978/12/05 | 1.7 | 0.00 | 9.44 | 1.30 | 3.49 | 0 | 4.79 | 0.01 | 2.23 | 0.04 |

Conceptually, *UQFLOW OTD* represents the fraction of *STORMF* generated on the day which actually exits the catchment on the day as surface runoff, i.e. calculated as *STORMF* x *QFRESP* = *UQFLOW OTD*. Therefore, on days when *STORMF* is generated, *UQFLOW OTD* contributes to the *UQFLOW* for the day, however, the *UQFLOW* for the day may also include residual *STORMF* from previous days, i.e. as calculated from the *STORMF STORE* as explained above, which is conceptualised as interflow. Therefore, the difference between *UQFLOW* and *UQFLOW OTD* represents interflow, i.e. interflow = *UQFLOW* - *UQFLOW OTD*. Therefore, from the example above (Table 4.7), for the 04/12/1978, the *STORMF* is equal to the *STORMF STORE* and therefore the *UQFLOW OTD* is the same as the *UQFLOW* for the day and there is no interflow contributing to *UQFLOW*. For the 05/12/1978, no *STORMF* is generated and therefore the *UQFLOW OTD* is 0 mm, residual *STORMF* from the previous day, however, is carried over to the *STORMF STORE*, and therefore the *UQFLOW* for the day is 3.49 mm. The

*UQFLOW* for the day is therefore completely comprised of interflow, i.e. since interflow = *UQFLOW* - *UQFLOW OTD*.

Based on this revised conceptualisation, the use of *STORMF* in Equation 4.3 was replaced with *UQFLOW OTD*, which represents the fraction of *STORMF* generated on the day which actually exits the catchment on the day as surface runoff. The difference between *UQFLOW* and *UQFLOW OTD*, which is conceptualised as interflow as explained above, is then calculated and added to the baseflow component of the peak discharge computation, however, conceptualised as interflow. In this revised approach, interflow has been incorporated into the original *ACRU* baseflow peak discharge equation (Equation 4.7) as follows:

$$BFIq_p = \frac{\left(\frac{BF_i + BF_{(i-1)}}{2} + I\right) \times A \times 1000}{24 \times 3600} \qquad (4.8)$$

where

$BFIq_p$ = baseflow and interflow contribution to total daily peak discharge [$m^3.s^{-1}$]

$I$ = interflow (*UQFLOW* - *UQFLOW OTD*) [mm].

Table 4.8 summarises how peak discharge is calculated applying the revised approach suggested, i.e. once again using the example above (Table 4.5).

Table 4.8 Revised peak discharge computation developed for the *ACRU* model, as applied to the Cathedral Peak example events, when applying the CSM system developed

| Column No. | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
|---|---|---|---|---|---|---|---|---|
| DATE | *RFL* (mm) | *STORMF* (mm) | *UBFLOW* (mm) | *UQFLOW* (mm) | *UQFLOW OTD* (mm) | $q_p$ *UQFLOW OTD* - Equation 4.4 ($m^3/s$) | $BFIq_p$ - Equation 4.9 ($m^3/s$) | *QPEAK* revised *ACRU* ($m^3/s$) |
| 1978/12/04 | 50.8 | 14.99 | 1.04 | 5.55 | 5.55 | 1.30 | 0.02 | 1.32 |
| 1978/12/05 | 1.7 | 0.00 | 1.30 | 3.49 | 0.00 | 0.00 | 0.05 | 0.05 |

For the 04/12/1978, the *UQFLOW OTD* (Column 5 - Table 4.8), i.e. 5.55 mm, is used with Equation 4.3 to estimate the contribution to *QPEAK* from surface runoff (Column 6 - Table 4.8), i.e. 1.30 $m^3/s$ for this particular day. *UQFLOW OTD* (Column 5 - Table 4.8) is then subtracted from the *UQFLOW* for the day (Column 4 - Table 4.8), i.e. 5.55 – 5.55 = 0 mm in this case, since there is no residual *STORMF* from previous days contributing to *UQFLOW*. The current ($BF_i$) and previous ($BF_{(i-1)}$) days *UBFLOW* is then used with Equation 4.8 to calculate the baseflow/interflow contribution to *QPEAK* (Column 7 - Table 4.8), 0.02 $m^3/s$ in this case. *QPEAK* (Column 8 - Table 4.8) is then obtained by combining the surface runoff contribution (Column 6 - Table 4.8) with the baseflow/interflow contribution (Column 7 - Table 4.8). For the 05/12/1978 the *UQFLOW OTD* (Column 5 - Table 4.8) is used with Equation 4.3 to estimate the contribution to *QPEAK* from surface runoff (Column 6 - Table 4.8), i.e. 0 $m^3/s$ for this particular day. *UQFLOW OTD* (Column 5 - Table 4.8) is then subtracted from the *UQFLOW* for the day (Column 4 - Table 4.8), which includes residual *STORMF* from the previous day, i.e. 3.49 – 0 = 3.49 mm in this case. This residual *STORMF* for the day is conceptualised as interflow and is added to the baseflow as represented in Equation 4.8, and determines the baseflow/interflow contribution to *QPEAK* (Column 7 - Table 4.8), 0.05 $m^3/s$ in this case. *QPEAK* (Column 8 - Table 4.8) is then once again obtained by adding the surface runoff contribution (Column 6 - Table 4.8) to the baseflow/interflow contribution (Column 7 - Table 4.8).

Table 4.9 summarises the results obtained when applying the current *ACRU* peak discharge computation (Table 4.6) and the revised *ACRU* peak discharge computation (Table 4.8) to that of the observed peak discharge for easy comparison. The results in Table 4.9 clearly show that the revised peak discharge computation provides a better estimate of the observed peak discharge.

Table 4.9 Summary of results obtained from the current and revised *ACRU* peak discharge computation compared to the observed peak discharges, for the Cathedral Peak example events, when applying the CSM system developed

| Column No. | 1 | 2 | 3 |
|---|---|---|---|
| DATE | *QPEAK* current *ACRU* ($m^3/s$) | *QPEAK* revised *ACRU* ($m^3/s$) | Observed Peak Discharge ($m^3/s$) |
| 1978/12/04 | 3.58 | 1.32 | 0.70 |
| 1978/12/05 | 0.01 | 0.05 | 0.04 |

Applying the revised peak discharge computation corrects the volume inconsistency currently applied in the *ACRU* peak discharge estimation and ensures that the same volume of total simulated streamflow (*USFLOW*) on a particular day is used to calculate the total peak discharge for the day (*QPEAK*), i.e. both the stormflow and baseflow/interflow contributions to peak discharge. In addition, the revised stormflow volumes (*UQFLOW OTD*) used in the stormflow peak discharge equations are conceptually correct since these equations, derived from the original SCS (1956) stormflow equations, estimate the surface runoff contribution to peak discharge. Consequently, since the *STORMF* generated on a given day in *ACRU* is partitioned into *UQFLOW* and a delayed stormflow response, conceptualised as interflow, hence it is not conceptually correct to use *STORMF* in the computations. Conceptually, the *UQFLOW OTD* is the surface runoff contribution to the daily peak discharge on the day of the event, and any residual *STORMF* from previous days, is conceptualised as interflow which is added to the baseflow component of the peak discharge computation.

The design daily peak discharges for Cathedral Peak IV (V1H005) and DeHoek / Ntabamhlope (V1H015), applying both the current peak discharge computation and the revised method described above are shown in Figure 4.6 and Figure 4.7, respectively. As indicated in the figures the revision to the peak discharge computation substantially improved the peak discharge simulations. The design peak discharges for the Cathedral Peak IV (V1H005) Catchment, applying both the CSM system and the default implementation of the *ACRU* model, remain very similar when applying the revised peak discharge computation, due to the similarities in the *QFRESP* values. With respect to the DeHoek / Ntabamhlope (V1H015) Catchment, however, there is a considerable difference in the design peak discharges obtained, i.e. when applying the revised peak discharge computation with the CSM system compared to the default implementation of the *ACRU* model. This is as a result of the differences in the *QFRESP* values for this catchment. When applying the current peak discharge computation in the *ACRU* model, the *QFRESP* parameter does not impact the peak discharge simulation as all the *STORMF* generated from an event is used in the stormflow peak discharge computation. As a result, the design peak discharges when applying the CSM system and the default implementation of the *ACRU* model are very similar (Figure 4.7), despite substantial differences in the design streamflow volumes (Figure 4.5). When applying the revised peak discharge computation, however, the *UQFLOW OTD* is used in the stormflow peak discharge computation and consequently *QFRESP* has a direct impact on the simulated peak. As a result, the design peak discharges when applying the CSM system and the default implementation of the *ACRU* model are considerably different (Figure 4.7) and match the trend of those obtained for the design streamflow volumes (Figure 4.5). The results in Figure 4.7, however, suggest that the most accurate design peak discharges simulated, i.e. compared to those obtained from the observed data, are obtained when applying the revised peak discharge computation procedure and the default implementation of the *ACRU* model. This, however, is not the case since the design streamflow volumes are substantially under-simulated when applying the default implementation of the *ACRU* model (Figure 4.5). Consequently, the closer fit to the observed peak discharges using the default *ACRU* implementation is for the wrong reason, since the simulated peak discharges are directly dependent on the simulated streamflow volumes.

In summary, improved peak discharges are obtained in the two catchments when applying both the CSM system and the default implementation of the *ACRU* model, with the revised peak discharge computation. Despite the substantial improvements, however, a general over-simulation of the peak discharges is still evident for both catchments, particularly in the cases when the design streamflow volumes are most similar to the observed design streamflow volumes. This is likely attributed to one or a combination of the following: (i) the surface runoff contribution to peak discharge being too high, i.e. the volume of *UQFLOW OTD* is too large and *QFRESP* possibly needs to be reduced further, (ii) incorrect estimation of catchment lag time, and (iii) the inability of Equation 4.3 (the design stormflow peak discharge equation) to account for the actual distribution of daily rainfall, (i.e. the rainfall intensity on the day), with the simplifying assumption that the effective storm duration ($\Delta D$) is equal to the catchment's time of concentration, which is empirically related to lag time.

The results obtained for all verification catchments, as presented for Cathedral Peak IV (V1H005) and DeHoek / Ntabamhlope (V1H015), excluding the Lambrechtsbos B (G2H010) Catchment, are summarised in Figure 4.8 – Figure 4.11. Owing to particularly poor results obtained for the Lambrechtsbos B (G2H010) Catchment and challenges associated with modelling this catchment, it was excluded from the analysis, since the inclusion of the results from this catchment significantly skews the statistics. To indicate this and to briefly summarise the results obtained from the Lambrechtsbos B (G2H010) catchment, the NSE values obtained from the CSM system and default implementation of the *ACRU* model in terms of Daily Streamflow Volumes (DyV) was -3.44 and -4.20, respectively. This is significantly lower than the average NSE values obtained from all catchments, excluding Lambrechtsbos B (0.45 and 0.41, respectively), as summarised in Figure 4.8. Similarly, the NSE values for Lambrechtsbos B obtained from the CSM system and default implementation of the *ACRU* model in terms of

Daily Peak Discharges (DyQp) applying the Current peak discharge computation procedure was -277.66 and -925.05, respectively. This is once again significantly lower than the average NSE values obtained from all catchments, excluding Lambrechtsbos B (Figure 4.8). In summary, the poor results obtained for Lambrechtsbos B are attributed to the following: (i) the driver rainfall stations being poorly representative of the catchment rainfall (Royappen *et al.*, 2002), with raingauges situated lower down in the catchment and with no gauges at higher elevations in the catchment, where it is documented that there is a strong altitudinal variation in rainfall, i.e. with the upper reaches of the catchment being extremely steep (Scott *et al.*, 2000; Gush *et al.*, 2002), (ii) deep groundwater recharge bypassing the gauging weir and water exiting the catchment into the adjacent Lambrechtsbos A Catchment (Gush *et al.*, 2002).

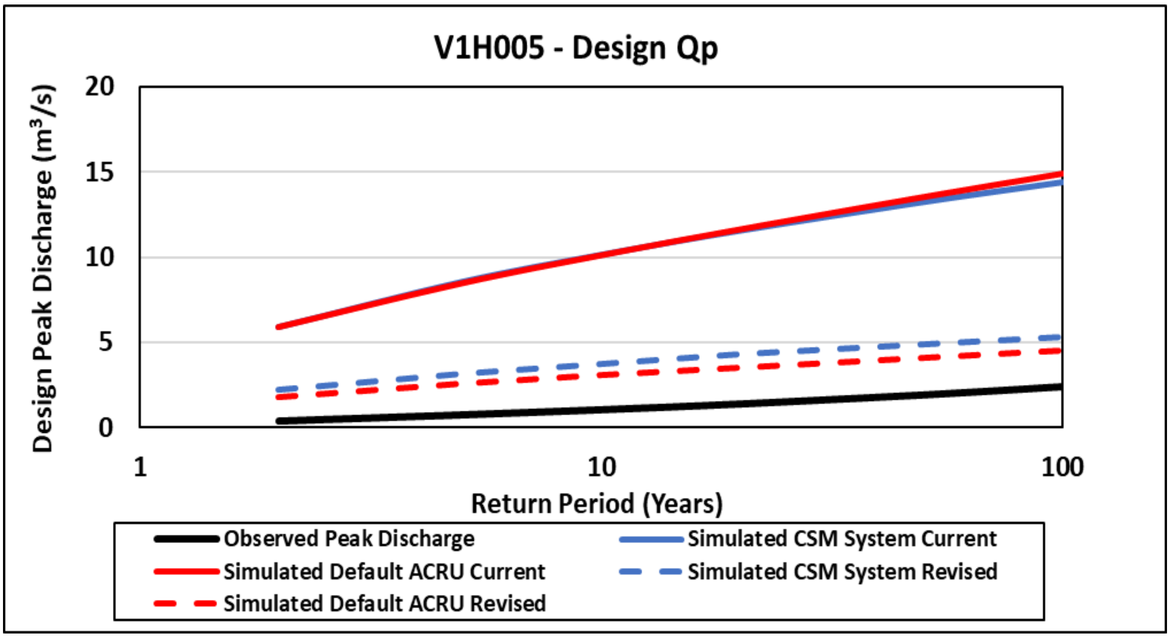

Figure 4.6 Design peak discharges (Qp) for the Cathedral Peak IV (V1H005) Catchment applying both the current and revised peak discharge computation

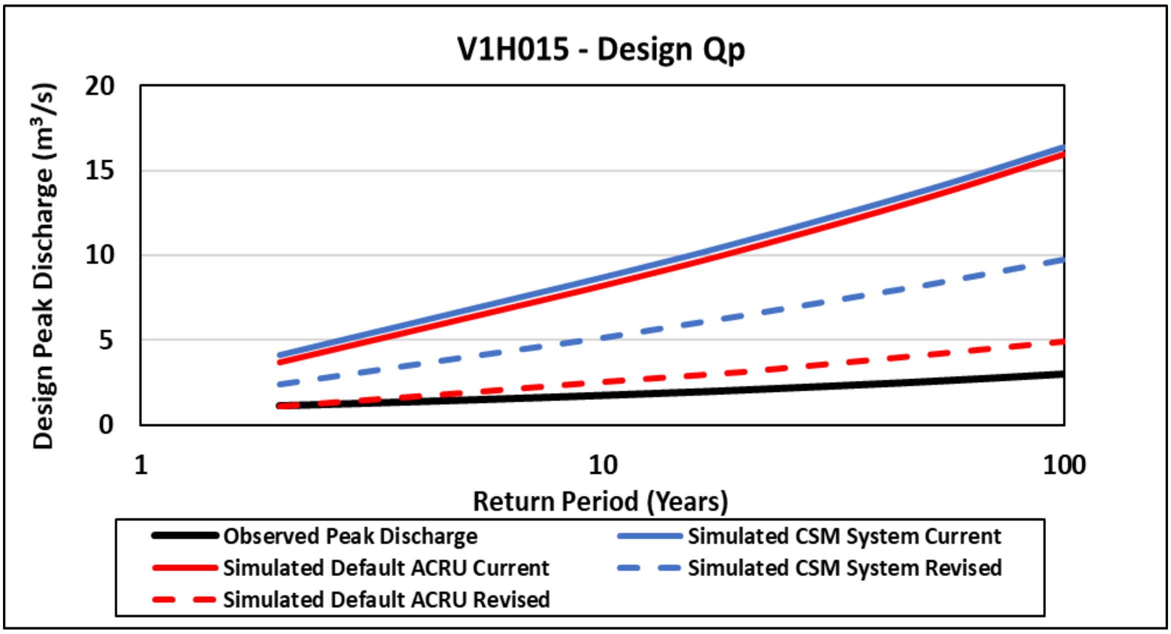

Figure 4.7 Design peak discharges (Qp) for the DeHoek / Ntabamhlope (V1H015) Catchment applying both the current and revised peak discharge computation

As indicated in Figure 4.8, the CSM system provides the most accurate results overall in terms of daily streamflow volumes for all verification catchments, with NSE, Coefficient of Determination (RSQ) and Regression Slope values all better than those obtained for the default implementation of the *ACRU* model. In terms of daily peak discharges (Figure 4.9), it is evident that extremely poor NSE values and high Regression Slope values are obtained for both the CSM system and default implementation of the *ACRU* model when applying the current peak discharge computation procedure. The NSE and Regression Slope values are, however, better for the CSM system, -37.29 and 2.98 respectively, compared to the default implementation of the *ACRU* model, -55.02 and 3.43 respectively. The RSQ values are very similar for both scenarios when applying the current peak discharge computation procedure. The NSE and Regression Slope values are substantially better for both scenarios when applying the revised peak discharge computation procedure. The RSQ values for both scenarios are also better, however, the improvement is not as substantial (Figure 4.9). In terms of the revised peak discharge computation, however, the NSE and Regression Slope values are slightly better for the default implementation of the *ACRU* model compared to the CSM system, the results are however similar (Figure 4.9). The RSQ values are, once again, very similar for both scenarios when applying the revised peak discharge computation procedure (Figure 4.9).

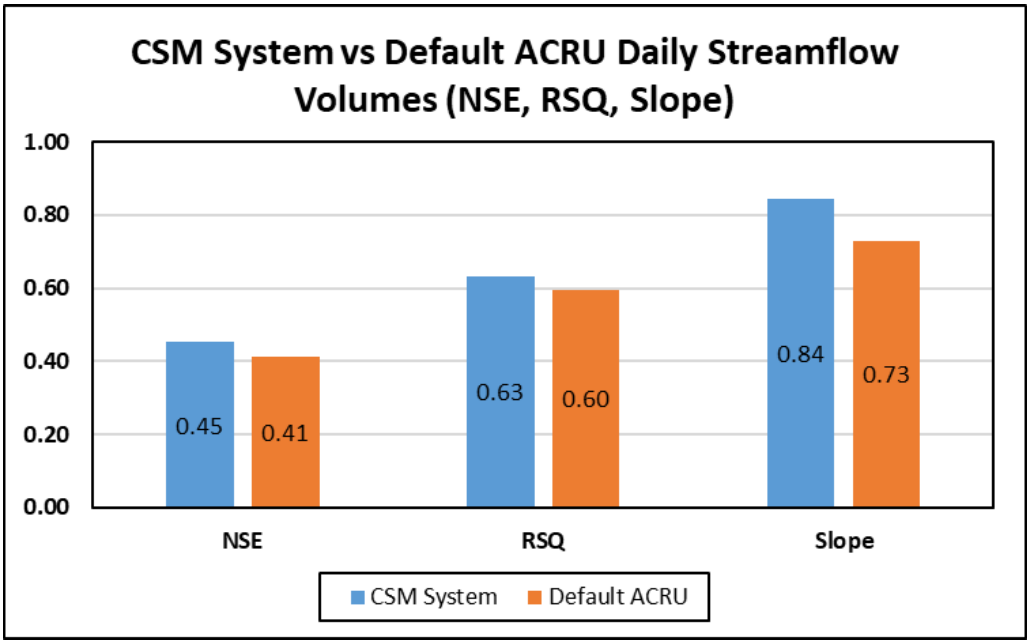

Figure 4.8 Summary of NSE, RSQ and Regression Slope values obtained for all verification catchments, excluding Lambrechtsbos B (G2H010), for simulated versus observed Daily Streamflow Volumes (DyV)

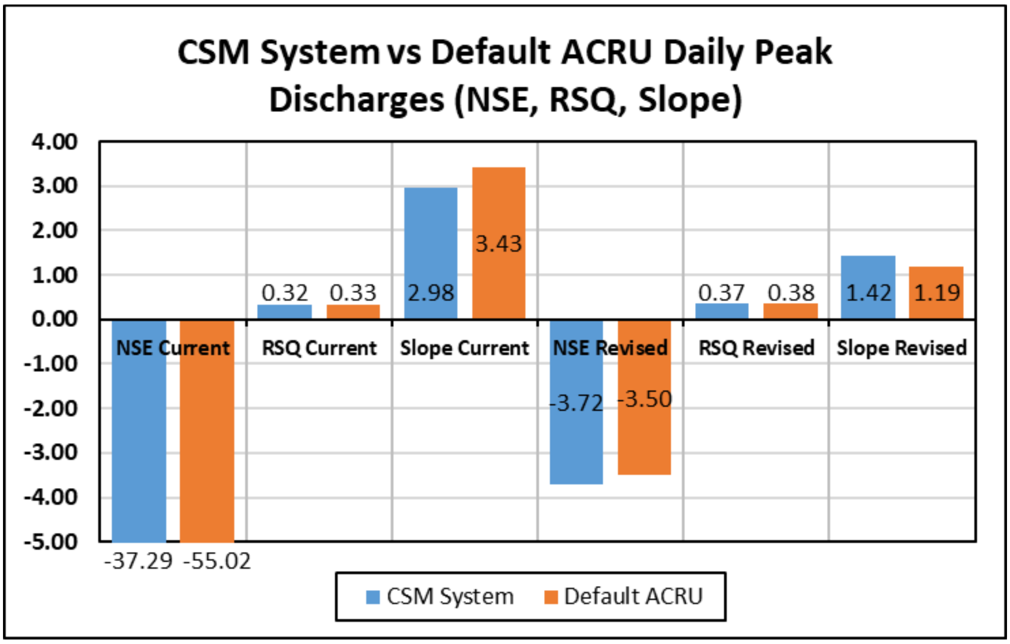

Figure 4.9 Summary of NSE, RSQ and Regression Slope values obtained for all verification catchments, excluding Lambrechtsbos B (G2H010), for simulated versus observed Daily Peak Discharges (DyQp), applying both the Current and Revised peak discharge computation procedure

A similar trend to the NSE, RSQ and Regression Slope values is reflected in the MARE/MRE values. In terms of design streamflow volumes (Figure 4.10) the MARE is higher (worse) for the default implementation of the *ACRU* model compared to the CSM system, 0.39 and 0.25 respectively. The MRE for both scenarios is lower than the MARE, indicating a combination of both under and over-simulation of design streamflow volumes. The MRE, however, is lower and negative (-0.08) for the default implementation of the *ACRU* model compared to the higher positive value (0.14) obtained for the CSM System, indicating a greater tendency of the default implementation of the *ACRU* model to under-simulate design streamflow volumes (Figure 4.10). This trend is directly translated to the MARE/MRE values in terms of design peak discharges (Figure 4.11). Since the default implementation of the *ACRU* model tends to under-simulate design streamflow volumes in general, the design peak discharge MARE and MRE values for this configuration, when applying the revised peak discharge computation procedure, are lower (1.49 and 1.29, respectively) than those obtained for the CSM System (1.76 and 1.75, respectively). The better (lower) MARE and MRE values for the default implementation of the *ACRU* model, when applying the revised peak discharge computation procedure, are therefore for the wrong reason and are not consistent with the under-simulated design streamflow volumes. The results from Figure 4.11 also confirm that the current peak discharge computation procedure is inadequate and produces extremely over simulated design peak discharges for both scenarios.

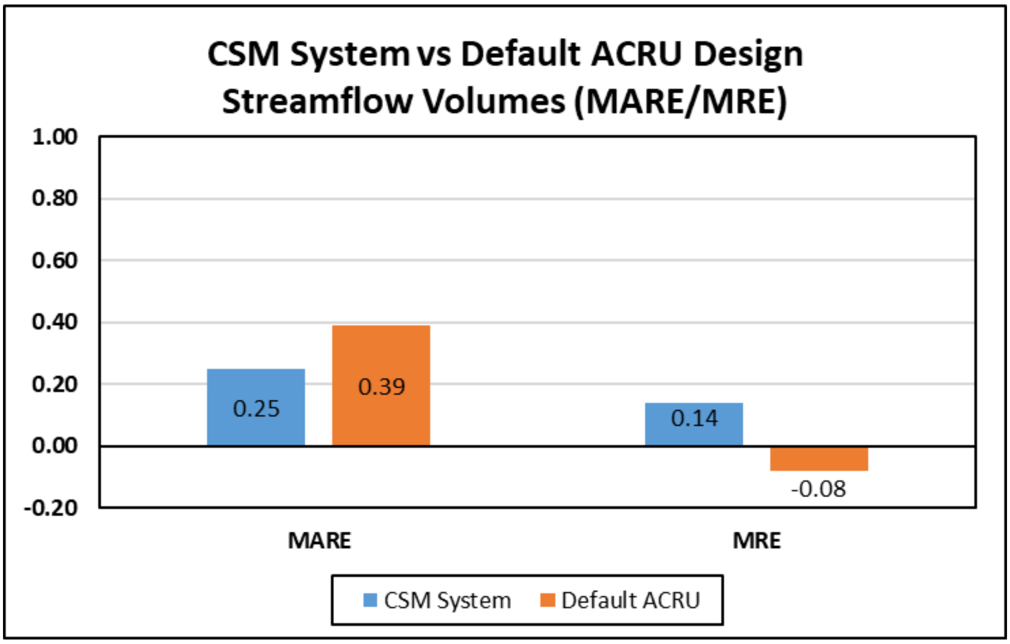

Figure 4.10 Summary of MARE and MRE values obtained for all verification catchments, excluding Lambrechtsbos B (G2H010), for simulated versus observed Design Streamflow Volumes (DnV)

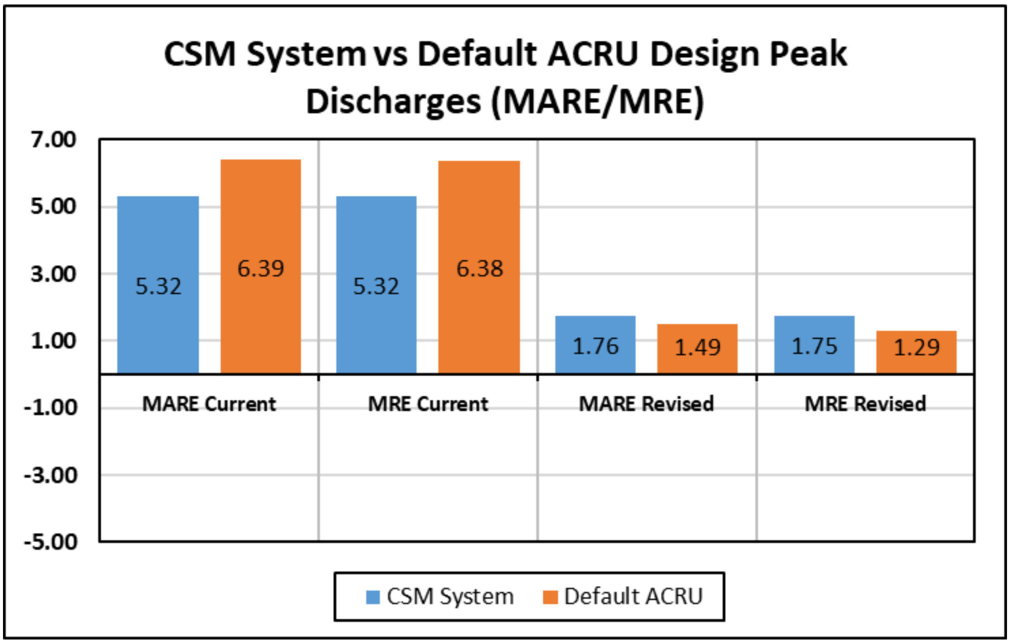

Figure 4.11 Summary of MARE and MRE values obtained for all verification catchments, excluding Lambrechtsbos B (G2H010), for simulated versus observed Design Peak Discharges (DnQp), applying both the Current and Revised peak discharge computation procedure

In summary, in terms of overall performance for all verification catchments, excluding the Lambrechtsbos B (G2H010) Catchment, the CSM system provides better results in terms of daily streamflow volumes (Figure 4.8) and design streamflow volumes (Figure 4.10) compared to the default implementation of the *ACRU* model. The individual results for each catchment are provided in Appendix F (Chapter 15). The revised peak discharge computation procedure described in this chapter provides a substantially better estimate of daily and design peak discharges for both scenarios. Overall, considering both daily and design streamflow volumes and peak discharges, the CSM system provides the most accurate results and motivates for further development and assessment of the CSM system. In addition, the ability of the CSM system to account for differences in hydrological responses for different, soils, land management practices and hydrological conditions, which are used to parameterise the *QFRESP* and *SMDDEP* parameters in *ACRU*, which are currently set to default values, is a major advantage over the default implementation of the *ACRU* model.

Lastly, despite the improvement in the simulated peak discharges obtained when applying the revised peak discharge computation procedure, a significant general over-simulation of the peak discharges is still evident, which requires further investigation.

## 4.6 Conclusions and Recommendations

In this chapter the results obtained from application of a CSM system developed for DFE in South Africa, using the *ACRU* model, are compared to those obtained from the current default implementation of the *ACRU* model. Difficulties associated with obtaining data and the poor quality of data in South Africa are highlighted, which was a significant challenge in this study, and is an issue that urgently needs to be addressed. In future, there is a dire need to collate, error check and standardise data from various sources into a single and easily obtainable database. If this is not performed timeously this valuable data from research catchments, that is irreplaceable, will be lost. This is particularly relevant to the sub-daily data which is extremely scarce in the country.

The initial results indicated that reasonable daily streamflow volumes and design streamflow volumes are simulated when applying both the CSM system developed and the default implementation of the *ACRU* model, within the current *ACRU* structure and computational procedures. Daily peak discharges and design peak discharges, however, were significantly over-simulated. Further investigation of the computation of peak discharge in the current *ACRU* model structure highlighted an inconsistency between daily simulated stormflow volumes and the volume of stormflow used in the daily stormflow peak discharge equation. Therefore, revisions were made to the calculation of peak discharge in the model, correcting the volume imbalance, which significantly improved the results. Overall, considering both daily and design streamflow volumes and peak discharges, the CSM system was identified to provide the most accurate results, which motivates for further development and assessment of the CSM system. Over-simulation of the daily and design peak discharges in general, however, was still evident for both the CSM system and the default implementation of the *ACRU* model. This was attributed to one or a combination of the following: (i) the surface runoff contribution to peak discharge still being too high, (ii) incorrect estimation of catchment lag time, and (iii) the inability of Equation 4.3 (the design stormflow peak discharge equation) to account for the actual distribution of daily rainfall, i.e. the rainfall intensity, on a given day.

The CSM system described and assessed in this chapter provides a consistent methodology to estimate the *QFRESP* and *SMDDEP* parameter values for a catchment, based on the land cover and soils information obtained for the catchment. Therefore, the parameters may be adjusted for different scenarios, e.g. simulating worst-case scenarios to obtain conservative design flood estimates, i.e. for structures with high hazard potential. This is identified and highlighted as a major advantage of the CSM system developed compared to the current default implementation of the *ACRU* model, where these parameters are generally set to fixed default values. In conclusion, however, regardless of how the *QFRESP* and *SMDDEP* parameter values are estimated, the revision applied to the *ACRU* peak discharge computation in this chapter should be applied in all future applications of the *ACRU* model in order to provide more realistic and accurate peak discharge estimates. Therefore, if an alternative or improved method to estimate *QFRESP* and *SMDDEP* values is developed, the revision to the peak discharge computation documented in this chapter should still be adopted. The simulation of daily streamflow from a catchment in the *ACRU* model is very sensitive to these parameters and therefore obtaining a best estimate of them is essential and should be considered carefully. Since these parameters in the CSM system have been derived from SCS-SA *CNs*, which vary significantly with soils and land cover, particular care in obtaining accurate soils and land cover information is recommended when applying the CSM system developed in this study.

In order to investigate the general over-simulation of the daily and design peak discharges, the next critical step is to determine what the *ACRU* stormflow peak discharge computation is most sensitive to, i.e. simulated stormflow volumes, the estimated catchment lag time, or the distribution of daily rainfall, i.e. rainfall intensity. This information may then be used to further improve the simulation of peak discharges in the *ACRU* model and the CSM system. This is addressed and investigated in the next chapter (Chapter 5).

# 5. PERFORMANCE AND SENSITIVITY ANALYSIS OF THE SCS-BASED PEAK DISCHARGE ESTIMATION IN THE *ACRU* MODEL

This chapter assesses the performance and sensitivity of the SCS-based peak discharge estimation procedures as implemented in the *ACRU* model for two case study catchments, and includes an assessment and comparison of both the single and incremental Unit Hydrograph approaches.

## 5.1 Introduction

In Chapter 4 the performance of the CSM system developed and described in Chapter 3 was compared to that of the current default implementation of the *ACRU* model. The CSM system developed in the study was found to produce more accurate results and provides a consistent methodology to estimate the *QFRESP* and *SMDDEP* parameter values for a catchment, based on the catchment land cover and soils information. Consequently, the CSM system described in Chapter 3 and assessed in Chapter 4 is used for the investigations performed in this chapter and all subsequent chapters. The CSM system developed in this study performed well in terms of reproducing simulated daily streamflow volumes and design streamflow volumes, however, the daily peak discharges and design peak discharges were initially significantly over-simulated. The major reason for this extreme over-simulation was identified to be as a result of using all the stormflow (*STORMF*) generated from a rainfall event in the stormflow peak discharge estimation, and not the actual stormflow (*UQFLOW OTD*) which leaves the catchment on the same day as the storm, as described in Chapter 4. *STORMF* was replaced with *UQFLOW OTD* in the stormflow peak discharge computation, which significantly improved the results. A general over-simulation of the peak discharges, however, was still evident. This was attributed to one or a combination of the following: (i) the stormflow contribution to peak discharge still being too high, (ii) incorrect estimation of catchment lag time, and (iii) the inability of the single Unit Hydrograph (UH) approach to account for the distribution of daily rainfall on a given day, i.e. the rainfall intensity. The single UH design stormflow peak discharge equation (Equation 4.3), referred to as the “single UH approach” from this point on, was used in the initial assessment (Chapter 4), since it is the default option applied with the *ACRU* model. There is, however, a need to assess and compare the performance of both the single UH approach and the incremental triangular unit hydrograph approach (Equation 4.1), referred to as the "incremental UH approach" from this point on.

When applying the single UH approach, a single triangular unit hydrograph is used to simulate the stormflow contribution to peak discharge, requiring only an estimate of the stormflow volume and the catchment lag time, as input to the approach. When applying the incremental UH approach, incremental triangular unit hydrographs are generated from a hyetograph and superimposed to simulate the stormflow contribution to peak discharge, requiring an estimate of the stormflow volume, catchment lag time, and the distribution of daily rainfall.

Therefore, the objectives of this chapter are to: (i) investigate the simulation, using the SCS-based approach, of the stormflow contribution to peak discharge in detail for two case study research catchments with high quality observed streamflow and sub-daily rainfall data, (ii) compare the results obtained from application of the single UH approach and the incremental UH approach, (iii) compare the simulated results when estimated parameter inputs are replaced with observed data, i.e. which will indicate how sensitive each approach is to each of the input parameters, and (iv) investigate if there is a relationship between the distribution of daily rainfall, i.e. rainfall intensity, and catchment lag time. The aim of this chapter is to identify priority components that have the most significant influence on the stormflow peak discharge computation and guide further research.

## 5.2 Case Study Catchments

The two case study catchments used in this chapter are the Cathedral Peak IV catchment (Gauging Weir ID V1H005), located on the Little Berg plateau of the Drakensberg mountain range, KwaZulu-Natal, near the town of Winterton, and the DeHoek / Ntabamhlope catchment (Gauging Weir ID V1H015), also located in KwaZulu-Natal approximately 20 km from the town of Estcourt in the foothills of the Drakensberg (Figure 4.1). Some general climatic and physiographical characteristics of the two catchments are provided in Table 5.1, as extracted from Table 4.1 in Chapter 4.

Weddepohl (1988) delineated South Africa into four rainfall intensity distribution regions and developed synthetic distributions for each region to disaggregate daily rainfall into a hyetograph. Region 1, with a Type 1 rainfall distribution, has the lowest rainfall intensity with rainfall more uniformly distributed throughout the day, while Region 4, with a Type 4 rainfall distribution, has the highest intensity with the majority of the daily rainfall falling within an hour, as depicted in Figure 5.1.

Table 5.1 Case study catchments climatic and physiographical characteristics

| **Catchments** | **Area (km$^2$)** | **MAP (mm)** | **Mean Altitude (m)** | **Revised SCS-SA Land Cover Class** | **Mean Slope (%)** | **SCS-SA Soil Group** | ***QFRESP*** | **Rainfall Intensity Region** | **$\bar{I}30$ (mm/h)** | **Schmidt-Schulze Lag (h)** |
|---|---|---|---|---|---|---|---|---|---|---|
| **Cathedral Peak IV (V1H005)** | 0.98 | 1264 | 2011 | Unimproved (Natural) Grassland in good condition | 32.7 | A/B | 0.37 | 4 | 81.89 | 0.47 |
| **DeHoek / Ntabamhlope (V1H015)** | 1.04 | 943 | 1512 | Unimproved (Natural) Grassland in good condition | 17.0 | B | 0.59 | 3 | 56.58 | 0.58 |

Using a map of the rainfall distribution regions for South Africa extracted from Schulze *et al.* (2004), the rainfall intensity region for each catchment was identified, as summarised in Table 5.1. This was required to calculate $\bar{I}_{30}$, i.e. the 2-year return period 30-minute rainfall intensity, as needed to estimate the lag time using the Schmidt and Schulze (1984) lag equation (Equation 4.4). To calculate $\bar{I}_{30}$ an estimate of the 2-year return period maximum 1-day rainfall is multiplied by a multiplication factor defined for each region, available from Schulze (1995). All the information in Table 5.1 was extracted from Table 4.1 (Chapter 4), with details about how the information was obtained provided in Chapter 4. Information about the data required to perform the analyses in this chapter, i.e. the data source, record length, periods with missing data and the consequent final event selection periods and number of events analysed, are summarised in Table 5.2, as extracted from Table 4.3 (Chapter 4). The data were collected, processed and error checked as detailed in Chapter 4 and used directly for the analyses in this chapter, as detailed below.

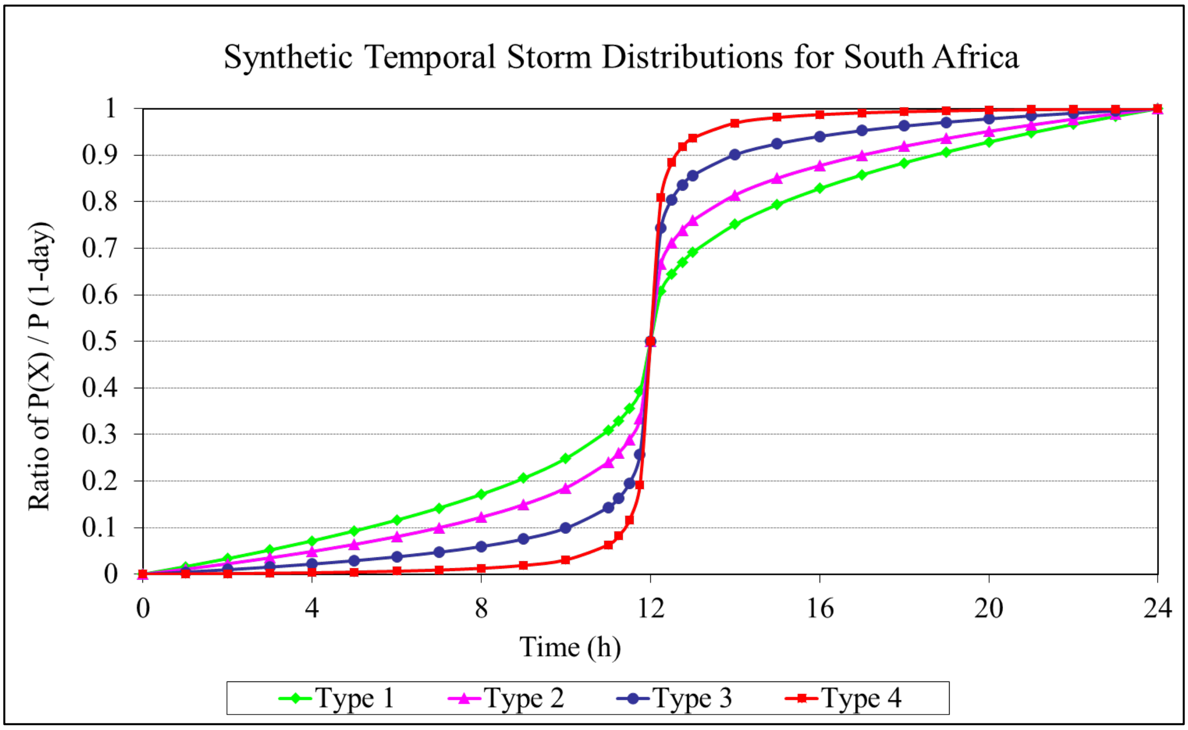

Figure 5.1 Time distributions of accumulated rainfall depth, P(X), divided by total daily rainfall depth, P(1-day), after Weddepohl (1988)

Table 5.2 Data source, record lengths and events analysed

| **Catchments** | **Data Source Streamflow** | **Record Length Streamflow** | **Data Source and ID of Hourly Rainfall** | **Record Length Hourly Rainfall** | **Final Event Selection Period (years)** | **Number of Events Analysed** | **Notes on Final Selection Period** |
|---|---|---|---|---|---|---|---|
| **Cathedral Peak IV (V1H005)** | CSIR (Mr A Chapman) | 1950 - 1992 | SAEON - C4_CD | 1972 – 1979 | 1974 – 1979 (5) | 20 | Rainfall data missing in 1972 and 1973, therefore only selected events between 1974 and 1979. |
| **DeHoek / Ntabamhlope (V1H015)** | CWRR | 1965 - 1993 | CWRR - N11 | 1977 – 1993 | 1979 – 1993 (14) | 17 | Large gap in observed streamflow record with no data for the period 1968 - 1978. Therefore, only selected events between 1979 and 1993. |

* CWRR - Centre for Water Resources Research; CSIR - Council for Scientific and Industrial Research; SAEON - South African Environmental Observation Network.

## 5.3 Methodology

The following methodology was applied in this chapter:

(i) The Flood Hydrograph Extraction Software (EX-HYD) developed by Görgens *et al.* (2007), and provided by Gericke (2018) was used to extract complete flood hydrographs from the primary streamflow data of the two catchments selected. The software identifies all significant events above a user defined threshold value. The default threshold value estimated by the model was used in this study. When applying the default value, the truncation level is set such that on average 5 peak events are selected per year (Denys *et al.*, 2006). The software is designed to estimate the start and end of each event, however, this is often not exact and sometimes single events are broken up into multiple events and thus each event had to be checked manually and adjusted if necessary.

(ii) For Cathedral Peak IV (V1H005), where only a short record of overlapping and consistent streamflow and sub-daily rainfall data were available, i.e. 1974 – 1979 (Table 5.2), the largest event for each year on record was firstly extracted and then the second largest, third largest, and so on, until a reasonable sample of 20 events was obtained. For DeHoek / Ntabamhlope (V1H015), the same procedure was followed, however, the record length was significantly longer, i.e. 1979 – 1993 (Table 5.2), and therefore the majority of the events selected were the annual maximum events and 17 events were finally extracted. It was essential to have both accurate short-duration (e.g. hourly) rainfall data, and primary streamflow data for each event. For this reason, in many cases events were excluded due to missing, erroneous or inconsistent rainfall or streamflow data. This resulted in the exclusion of the largest events on record for certain years. An additional requirement was that each event had to start and end within the time period from 08:00 to 08:00 the next day, i.e. to be consistent with the daily modelling output from the *ACRU* model. Consequently, significant time was spent on checking and verifying the data for each event selected. A lack of short-duration rainfall data, particularly consistent and accurate short-duration rainfall data, was a significant challenge to this study. This coupled with time constraints to complete the project resulted in the use of only two case study catchments. These catchments were selected since they were identified to have high quality data, with the short-duration rainfall stations being highly representative of the catchments.

(iii) A Hydrograph Analysis Tool (HAT), developed by Gericke in Microsoft Excel, and implemented by Gericke and Smithers (2017), was used to further analyse and process each of the events extracted using the EX-HYD software. This included: (i) a final check that each event hydrograph fell within the time period 08:00 to 08:00 the next day, i.e. the rise, peak and recession of the hydrograph all occur within this time period, (ii) separation of the event hydrographs into direct surface runoff and baseflow, and (iii) calculation of the time to peak ($T_P$) and corresponding lag time ($L$). The Nathan and McMahon (1990) method to separate direct surface runoff and baseflow, as recommended and implemented by Gericke and Smithers (2017), was applied in this study. This was essential in order to determine the actual observed direct surface runoff (stormflow) for each event to use in the *ACRU* stormflow peak discharge equations. As recommended and implemented by Gericke and Smithers (2017), the time to peak was calculated from the point on the hydrograph where the streamflow changes from nearly constant or steadily declining values to rapidly increasing values until the point where the peak discharge occurs. For multi-peaked events the total net rise of the hydrograph was used to calculate the time to peak, i.e. only the periods where the hydrograph ordinates are increasing are used, up to the point where the final peak discharge is reached, as detailed by Gericke and Smithers (2017). Applying the assumption defined by Gericke and Smithers (2017) that $T_P \approx T_C$, the observed lag time ($L$) for each event is calculated using Equation 4.2 (Chapter 4).

(iv) The *ACRU* simulation results obtained from the assessment of the CSM system in the Chapter 4, i.e. applying the revised peak discharge computation procedure, were used to provide the simulated stormflow volumes, i.e. *UQFLOW OTD*, required as input to the *ACRU* stormflow peak discharge equations.

(v) The Schmidt and Schulze (1984) lag equation was used to estimate the average catchment lag time for the two case study catchments, as summarised in Table 5.1.

(vi) Using all of the information above, the performance of the single UH approach, i.e. the default option in the *ACRU* model, as implemented in Chapter 4, was firstly investigated (Step 1). The following procedure was followed:

- Step 1.1, the simulated *UQFLOW OTD* from the *ACRU* model was used as input to the single UH approach along with the Schmidt and Schulze (1984) estimated lag time, to estimate the stormflow contribution to the peak discharge for the day, i.e. for each of the events extracted for the two case study catchments.
- Step 1.2, repeat Step 1.1, however, replace the Schmidt and Schulze (1984) estimated lag time, i.e. which remains constant for each event, with the observed lag time estimated for each event extracted from the observed event hydrographs.
- Step 1.3, use both the observed stormflow volume and observed lag time for each event to calculate the stormflow contribution to peak discharge.

(vii) The same procedure was followed to assess the performance of the incremental UH approach (Step 2), however, in this case the temporal distribution of daily rainfall was required. Therefore, the procedure was as follows:

- Step 2.1, the simulated *UQFLOW OTD* from the *ACRU* model was disaggregated into incremental stormflow volumes, based on hyetographs generated using the daily rainfall and one of four synthetic regionalised rainfall distributions (Figure 5.1) applicable to each catchment (Table 5.1). Incremental triangular UHs were then generated for each increment of stormflow volume, using the Schmidt and Schulze (1984) estimated lag time. The incremental UHs were then superimposed to provide a composite surface runoff hydrograph and final stormflow peak discharge estimate, as depicted in Figure 5.2. A program written in FORTRAN was used for these computations.
- Step 2.2, repeat Step 2.1, however, replace the synthetic regionalised rainfall distributions with the observed rainfall hyetographs for each event, and replace the Schmidt and Schulze (1984) estimated lag time with the observed lag time for each event.
- Step 2.3, use the observed stormflow volume, the observed rainfall hyetographs, and the observed lag time for each event to calculate the stormflow contribution to peak discharge.
- Step 2.4, use the *UQFLOW OTD* as the input for stormflow and keep this fixed, then use the observed rainfall hyetographs and Schmidt and Schulze (1984) estimated lag time for one set of computations, then change this to the synthetic regionalised rainfall distributions and the observed lag time. The objective of this assessment is to try to identify if the incremental UH approach is more sensitive to inaccurate estimates of daily rainfall distributions or to catchment lag times.

(viii) The results from each of the above analyses are then summarised for each catchment using both the Mean Relative Error (MRE), Equation 5.1, and the Mean Absolute Relative Error (MARE), Equation 5.2, between observed and simulated peak discharge values, i.e. from all the selected events, as follows:

$$MRE = \frac{1}{n}\sum_{i=1}^{n}\frac{Sim_i - Obs_i}{Obs_i} \tag{5.1}$$

$$MARE = \frac{1}{n}\sum_{i=1}^{n}\frac{|Sim_i - Obs_i|}{Obs_i} \tag{5.2}$$

where

$MRE$ = mean relative error (0 - ∞; objective is to minimise MRE),

$MARE$ = mean absolute relative error (0 - ∞; objective is to minimise MARE),

$Sim_i$ = simulated stormflow peak discharge, for event i [$m^3.s^{-1}$],

$Obs_i$ = observed stormflow peak discharge, for event i [$m^3.s^{-1}$].

$n$ = number of events.

(ix) The results are then compared and discussed.

(x) An additional investigation was performed using the observed data to identify if there is a relationship between the distribution of daily rainfall, i.e. rainfall intensity, and catchment lag time.

(xi) Conclusions are then drawn from the results and recommendations made for further research.

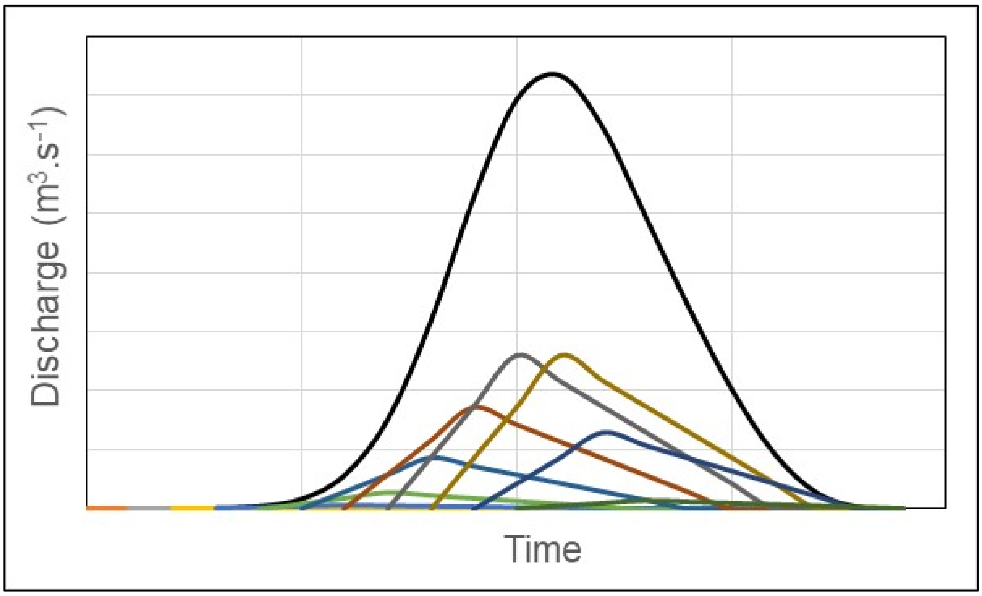

Figure 5.2 Generation of incremental UH's which are superimposed to provide a composite surface runoff hydrograph, after Schmidt and Schulze (1987a)

### 5.4 Results and Discussion

The results obtained from the assessment of both the single and incremental UH approaches are presented in this section, i.e. applying the methodology as described in Section 5.3. A detailed example of the results from application of the single UH approach, for a single event, is provided in Figure 5.3. S&S Lag in Figure 5.3 refers to the Schmidt and Schulze (1984) estimated lag time, and Obs Lag refers to the observed lag time. Similarly, Obs Q refers to the observed stormflow. The SCS triangular hydrographs, as depicted in Figure 5.3, were generated as follows: the single UH approach (Equation 4.3) was used to estimate the stormflow peak discharge. Then, applying the SCS synthetic hydrograph assumption (Schmidt and Schulze, 1987a) that 37.5% of the total surface runoff volume falls between the start of surface runoff and the stormflow peak discharge, and using the available estimates of the time to peak ($T_P$), the total base time ($T_B$) was calculated using the SCS synthetic triangular hydrograph relationship $T_B = 2.67T_P$. It is important to recall from Section 5.3 that $L$ and $T_P$ were related and calculated using Equation 4.2, and assuming that $T_P \approx T_C$, as defined by Gericke and Smithers (2017). Since the start time of surface runoff as estimated using the single UH approach cannot be determined, i.e. as it is a design approach and simply gives the peak for the day and does not specify the timing of the peak, the simulated triangular stormflow hydrographs presented below were assumed to start at the same time as the observed stormflow hydrograph. The hourly rainfall distribution for the day, although not applicable to the single UH approach, is also included to show the relationship between the observed rainfall and corresponding observed stormflow response.

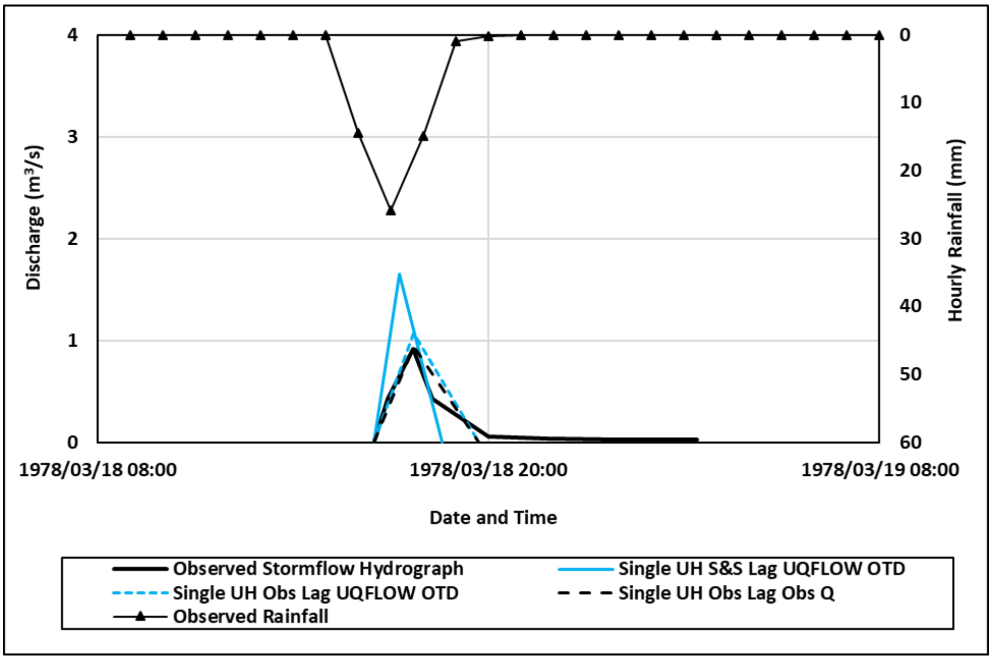

Figure 5.3 Observed stormflow hydrograph and simulated stormflow hydrographs obtained for a single event, at Cathedral Peak IV (V1H005), applying the single UH approach

As detailed in Section 5.3 – Step 1, the performance of the single UH approach was assessed using both observed (Obs *Q*) and simulated (*UQFLOW OTD*) stormflow volumes, with estimated (S&S Lag) or observed (Obs Lag) catchment lag times. From Figure 5.3 it is evident that using *UQFLOW OTD* and the estimated S&S Lag time results in an over-simulation of the stormflow peak discharge for this event (solid blue line), i.e. compared to the Observed Stormflow Hydrograph (solid black line). An improvement is observed when *UQFLOW OTD* and the Obs Lag time are used (dashed blue line), and this result is very similar to that obtained when both the Obs *Q* and Obs Lag time are used (dashed black line). The results indicate that *UQFLOW OTD* is a reasonable estimate of the stormflow volume for this event, and that the single UH approach is sensitive to the catchment lag time. For reference, the Obs Q for this event is 6.1 mm and the simulated *UQFLOW OTD* is 7.0 mm. The Obs Lag time for this event is 0.72 hours while the S&S Lag time is 0.47 hours.

A detailed example of the results obtained from application of the incremental UH approach, i.e. applying the methodology as described in Section 5.3 - Step 2, is depicted in Figure 5.4, using the same event used for the single UH approach above. The incremental UH approach was used to develop the composite stormflow hydrographs depicted in Figure 5.4, based on either the regionalised synthetic rainfall distribution defined for the region, i.e. the Type 4 rainfall distribution in this case, referred to as Rain T4 in Figure 5.4, or the observed rainfall hyetograph, referred to as Obs Rain in Figure 5.4. Obs Q, Obs L and S&S L are as defined above for the single UH approach. The incremental triangular hydrographs were obtained in the same manner as those obtained for the single UH approach above, lagged and superimposed to develop composite surface runoff hydrographs. The stormflow increments were determined based on the distribution of the daily rainfall used. The synthetic rainfall distributions developed by Weddepohl (1988) assume that 50% of the day's rainfall, i.e. defined as the period between 08:00 to 08:00 the next day, occurs in the first 12 hours of the day and the remaining 50% in the latter 12 hours of the day. Furthermore, the rainfall for each synthetic distribution is symmetrically distributed on either side of this mid-point (Figure 5.1). Therefore, as seen in Figure 5.4, the distribution of daily rainfall derived from the synthetic Type 4 rainfall distribution (Rain T4) is centered at the middle of the day (20:00) and is symmetrically distributed. The Obs Rain, which is similarly distributed to Rain T4 for this event (Figure 5.4), is not centered around the middle of the day with the majority of the rainfall and the peak occurring before the middle of the day (20:00). As a result, there is a shift in the timing of the composite stormflow hydrographs simulated when using Rain T4 compared to when the Obs Rain is used.

As investigated for the single UH approach above, and as detailed in Section 5.3 – Step 2, the performance of the incremental UH approach was assessed using both observed (Obs Q) and simulated (*UQFLOW OTD*) stormflow volumes and observed (Obs L) and estimated (S&S L) catchment lag times, however, in this case the distribution of daily rainfall was also accounted for. From Figure 5.4 it is evident that using *UQFLOW OTD*, the estimated S&S Lag time, and Rain T4 results in an over-simulation of the stormflow peak discharge for this event (solid blue line), i.e. compared to the Observed Stormflow Hydrograph (solid black line). An improvement is observed when *UQFLOW OTD*, the Obs Lag time and Obs Rain are used (dashed blue line), and this result is very similar to that obtained when all the observed inputs are used, i.e. Obs *Q*, Obs Lag and Obs Rain (dashed black line). The results once again indicate that *UQFLOW OTD* is a reasonable estimate of the stormflow volume for this event, and that the incremental UH approach is also sensitive to the catchment lag time.

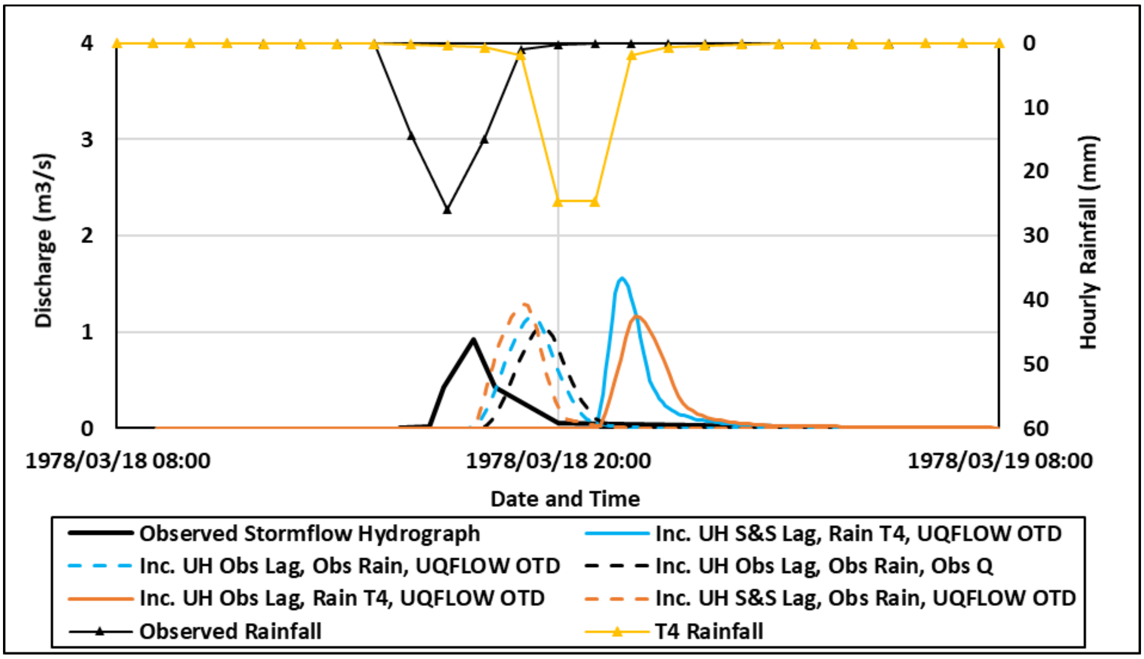

Figure 5.4 Observed stormflow hydrograph and simulated stormflow hydrographs obtained for a single event, at Cathedral Peak IV (V1H005), applying the incremental UH approach

The final two simulated stormflow hydrographs compare the sensitivity of the incremental UH approach to lag time and the distribution of daily rainfall individually, i.e. if the simulation where *UQFLOW OTD* is used in combination with the Obs Lag time and Obs Rain (dashed blue line) is considered and the Obs Rain is replaced with Rain T4 (solid orange line) there is no noticeable change in the stormflow peak discharge, however, there is a slight increase when the Obs Lag time is replaced with the estimated S&S Lag time (dashed orange line). Therefore, in this case and for this specific event, the incremental UH approach is more sensitive to the estimated S&S Lag time than Rain T4, i.e. the synthetic rainfall distribution. This, however, is as a result of the observed rainfall distribution being very similar to the synthetic T4 rainfall distribution for this particular event. The detailed results provided above for both the single UH approach and the incremental UH approach, for this single event at the Cathedral Peak IV (V1H005) Catchment, provide a graphical example of how the peak discharges and stormflow hydrographs were generated for each of the respective approaches. It is not practical to reproduce these results and graphical plots for all the events selected at both catchments, consequently, the results obtained from both catchments were summarised using the MARE and the MRE statistics as described in Section 5.3. The results for Cathedral Peak IV (V1H005) and DeHoek / Ntabamhlope (V1H015) are summarised in Figure 5.5 and Figure 5.6, respectively. The results when using *UQFLOW OTD* and Obs Q are both provided for comparison.

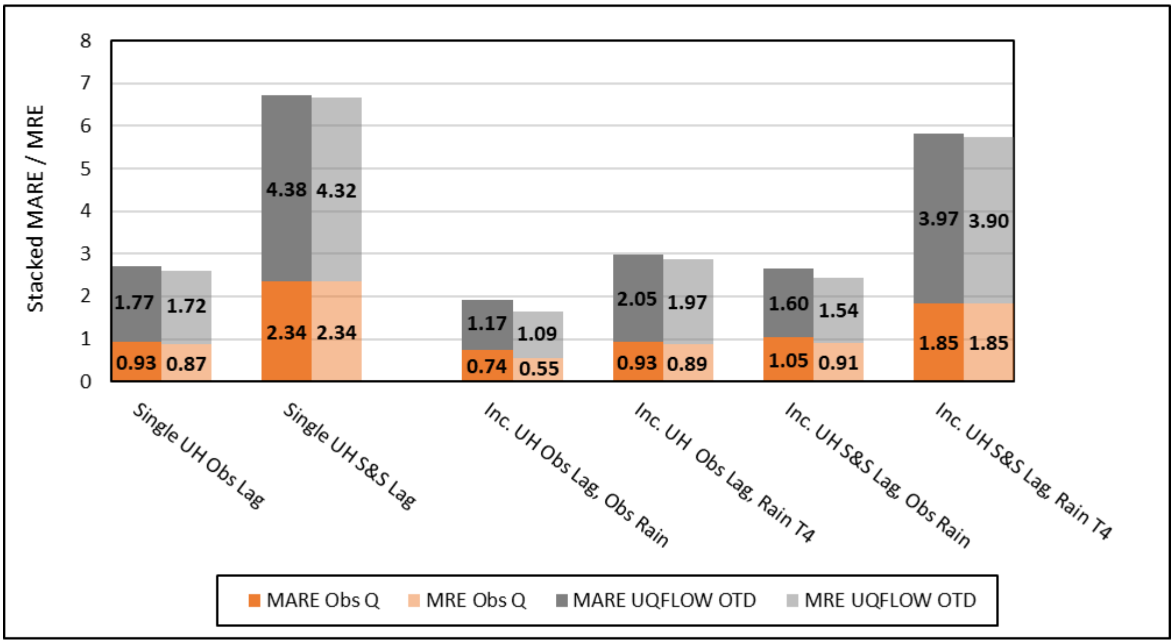

Figure 5.5 Cathedral Peak IV - MARE and MRE between observed and simulated stormflow peak discharges for both the single and incremental UH approaches

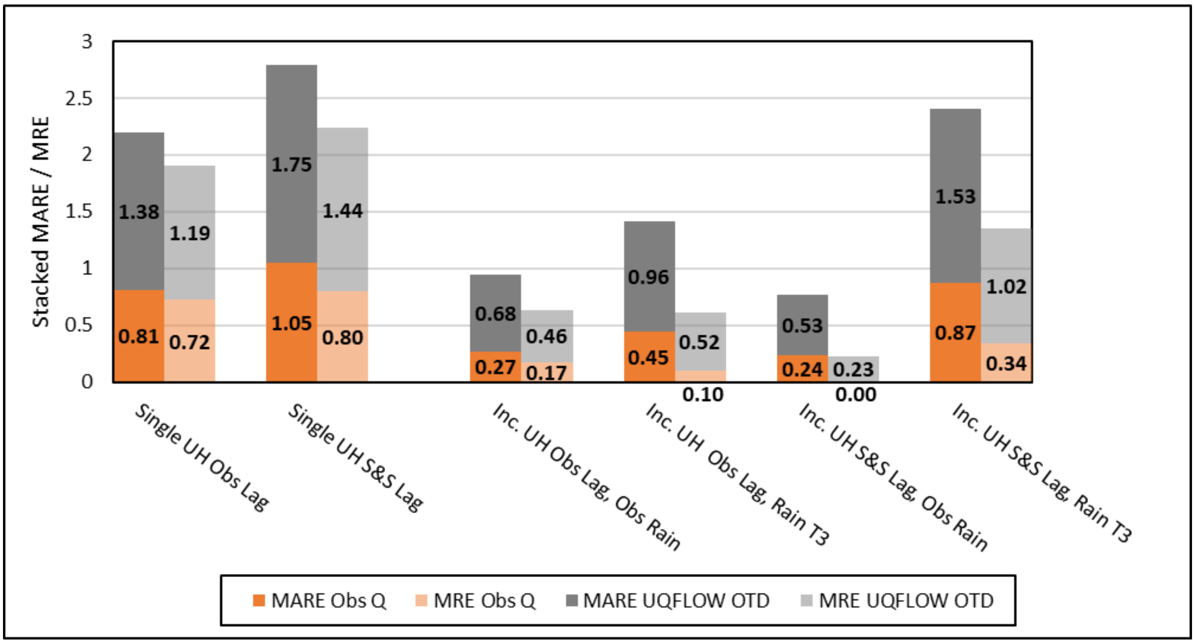

Figure 5.6 DeHoek / Ntabamhlope - MARE and MRE between observed and simulated stormflow peak discharges for both the single and incremental UH approaches

As indicated by the results presented in Figure 5.5 and Figure 5.6, the combinations where all the observed data were used as input to each of the respective approaches produces the lowest MARE values. This is logical and was expected since the observed data are the best estimate of the input parameters required for each approach. For example, for the Cathedral Peak IV Catchment, when applying the single UH approach the MARE is lowest when using the Obs Q and Obs Lag (0.93). Similarly, when applying the incremental UH approach, the MARE is lowest when using Obs Q, Obs Lag and Obs Rain (0.74). In addition, there is generally a consistent overestimation of the peak discharges for all scenarios, i.e. the MARE and MRE values are generally the same or very similar (Figure 5.5). Similarly, for the DeHoek / Ntabamhlope Catchment, when applying the single UH approach the MARE is lowest when using the Obs Q and Obs Lag (0.81). When applying the incremental UH approach, however, the MARE is lowest when using Obs Q, the S&S Lag and Obs Rain (0.24). This, however, is only slightly lower than that obtained when using Obs Q, Obs Lag and Obs Rain (0.27). The reason for this, however, is coincidental and is linked to the large range of Obs Lag time values for this catchment (0.15 – 2.6 hours). As indicated in Figure 5.7 there is generally a very slight overestimation of the peak discharges for this catchment when using all the observed inputs to the incremental UH approach, including the Obs Lag time, the correlation between observed and simulated peaks, however, is high ($R^2 = 0.74$). When replacing the Obs Lag with the S&S

Lag there is a greater tendency to underestimate the peak discharges, particularly for the highest peaks, and the correlation between observed and simulated peaks reduces by more than 50 % ($R^2$ = 0.32). The S&S lag equation therefore generally overestimates the catchment lag time, which reduces the majority of the peak discharge events to values closer to the observed peaks, purely by chance as a result of smoothing and averaging of the lag time which in reality is particularly erratic for this particular catchment. The MARE values, however, for these two scenarios are very similar and indicate that the S&S Lag is a reasonable estimate of the average catchment response time for this catchment. In addition, there is generally a combination of both over and underestimation of the peak discharges for all scenarios for this catchment, as indicated by the MARE and MRE values (Figure 5.6).

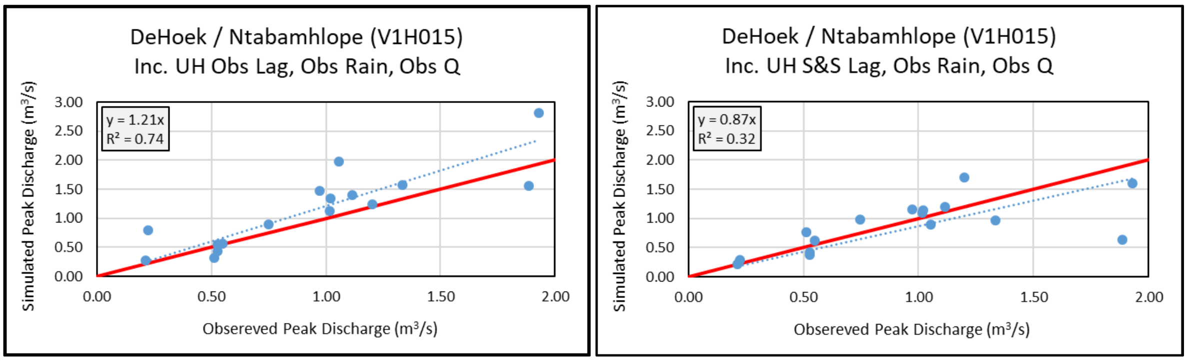

Figure 5.7 DeHoek / Ntabamhlope – Observed versus simulated scatter plot of peak discharges when using the incremental UH approach with all observed inputs (left) versus the same setup, however, replacing Obs Lag with S&S Lag (right)

For context, the range of Obs Lag time values obtained for Cathedral Peak IV was 0.36 – 1.68 hours, with an observed average of 0.90 hours, and an estimated S&S Lag time of 0.47 hours. If the observed average lag time were to be used in place of the estimated S&S Lag time, the over-simulation of stormflow peak discharges, as depicted in Figure 5.5, when applying the S&S Lag time would be reduced. The S&S estimated Lag time, however, is reasonable and provides a more conservative estimate, i.e. to rather overestimate peak discharge than underestimate, thereby accounting for more of the extreme cases. In terms of the DeHoek / Ntabamhlope catchment the range of Obs Lag time values obtained was 0.15 – 2.6 hours, with an observed average of 0.56 hours. This is very similar to the S&S Lag time (0.58 hours), therefore once again indicating that the estimated S&S Lag time provides a reasonable estimate of catchment lag time.

When replacing the Obs Q with the simulated *UQFLOW OTD* for both approaches, i.e. with the observed data for the remaining inputs, there is a relatively substantial increase in the MARE for both approaches. The average percentage increase in the MARE, for both catchments, for both the single and incremental UH approach is provided in Table 5.3. The results indicate that, on average, the MARE increases by 80 % for the single UH approach and by 105 % for the incremental UH approach when the Obs Q is replaced with *UQFLOW OTD*. Therefore, as identified in Chapter 4, the sensitivity of the SCS stormflow peak discharge equations to stormflow volumes is highlighted. Although the MARE increases for each of the approaches when using *UQFLOW OTD* in place of the Obs Q, the results are still acceptable and indicate that *UQFLOW OTD* is a reasonable estimate of the daily stormflow volume. In addition, *UQFLOW OTD* is currently the best estimate of daily stormflow volumes available in the *ACRU* model, i.e. as identified in Chapter 4, and is a significant improvement compared to the current use of all the *STORMF* generated from an event.

The average percentage increase in the MARE, for both catchments, for both the single and incremental UH approaches, when replacing observed inputs with estimated and/or synthetic inputs, is provided in Table 5.3, when using both Obs Q and *UQFLOW OTD*. The results indicate that the single UH approach is particularly sensitive to the catchment lag time with the MARE increasing by 91 % and 87 %, respectively, when the Obs Lag is replaced with the S&S Lag. In terms of the incremental UH approach, the results indicate that, on average, the approach is more sensitive to the distribution of daily rainfall compared to the catchment lag time, i.e. the average increase in the MARE when the Obs Rain is replaced with the synthetic rainfall distributions (Rain T3/T4) is 46 % (Obs Q) and 58 % (*UQFLOW OTD*), and only 27 % (Obs Q) and 29 % (*UQFLOW OTD*) when the Obs Lag is replaced with the S&S Lag, keeping all other inputs fixed. When simultaneously replacing both the Obs Rain and the Obs Lag with the synthetic rainfall distributions (Rain T3/T4) and the S&S Lag, the average increase in the MARE is 186 % (Obs Q) and 182 % (*UQFLOW OTD*), which is substantially higher than the combined percentage changes from the individual replacements of each of the two observed estimates, i.e. 46 % + 27 % = 73 % (Obs Q) and 58 % + 29 % = 87 % (*UQFLOW OTD*). Therefore, indicating a compounding of the error when both the rainfall distribution and catchment lag time are not accurately estimated.

Table 5.3 Average percentage increase in the MARE for both the single and incremental UH approaches, when replacing observed inputs with estimated and/or synthetic inputs, and between the results obtained from the single and incremental UH approaches

| From | To | Average % increase in MARE | |
|---|---|---|---|
| Single UH Obs Lag, Obs Q | Single UH Obs Lag, *UQFLOW OTD* | 80 | |
| Inc. UH Obs Lag, Obs Rain, Obs Q | Inc. UH Obs Lag, Obs Rain, *UQFLOW OTD* | 105 | |
| From | To | Obs Q | *UQFLOW OTD* |
| Single UH Obs Lag | Single UH S&S Lag | 91 | 87 |
| Inc. UH Obs Lag, Obs Rain | Inc. UH Obs Lag, Rain T3/T4 | 46 | 58 |
| Inc. UH Obs Lag, Obs Rain | Inc. UH S&S Lag, Obs Rain | 27 | 29 |
| Inc. UH Obs Lag, Obs Rain | Inc. UH S&S Lag, Rain T3/T4 | 186 | 182 |
| Inc. UH S&S Lag, Rain T3/T4 | Single UH S&S Lag | 24 | 12 |
| Inc. UH Obs Lag, Obs Rain | Single UH Obs Lag | 113 | 77 |

The average percentage increase in the MARE of Qp estimates between the results obtained from the incremental and single UH approaches, when using both observed versus estimated and/or synthetic inputs, is also provided in Table 5.3. On average, when using the estimated and/or synthetic inputs in both the single and incremental UH approaches the MARE is 24 % (Obs Q) and 12 % (*UQFLOW OTD*) higher for the single UH approach compared to the incremental UH approach. When using the observed inputs in both the single and incremental UH approaches the MARE is 113 % (Obs Q) and 77 % (*UQFLOW OTD*) higher for the single UH approach compared to the incremental UH approach. Therefore, regardless of whether observed or estimated and/or synthetic inputs are used, the incremental UH approach provides better results when compared to the single UH approach. The results, however, are substantially better for the incremental UH approach when accurate estimates of the input parameters are provided.

As detailed in Section 5.3, an additional investigation into the relationship between catchment lag time and rainfall intensity, i.e. the distribution of daily rainfall, was performed. Intuitively it was expected that with an increase in rainfall intensity there would generally be a reduction in the lag time, since rainfall has less time to infiltrate the soil, and therefore there is a more rapid stormflow response. For the two catchments investigated this was indeed identified to be the case, as indicated by the results depicted in Figure 5.8. The R value in Figure 5.8 is representative of rainfall intensity, it represents the ratio between the maximum 1 hour rainfall volume and the total daily rainfall volume, i.e. a value of 1 indicates that all the rainfall fell within 1 hour and therefore it was a very intense event, and a value close to zero indicates that the rainfall was more uniformly distributed throughout the day, i.e. low intensity. There is some scatter around the relationship, which may be attributed, but not limited, to antecedent soil water conditions, however, there is a clear inverse relationship between rainfall intensity and lag time. If a methodology to account for rainfall intensity on a day-to-day basis is developed and included within the *ACRU* model, relationships such as these may be useful to adjust estimated lag times based on the rainfall intensity. This is important since there is a relationship between the two and they both influence the simulation of the stormflow contribution to peak discharge. Furthermore, it provides an objective approach to account for the variability in lag time from event-to-event.

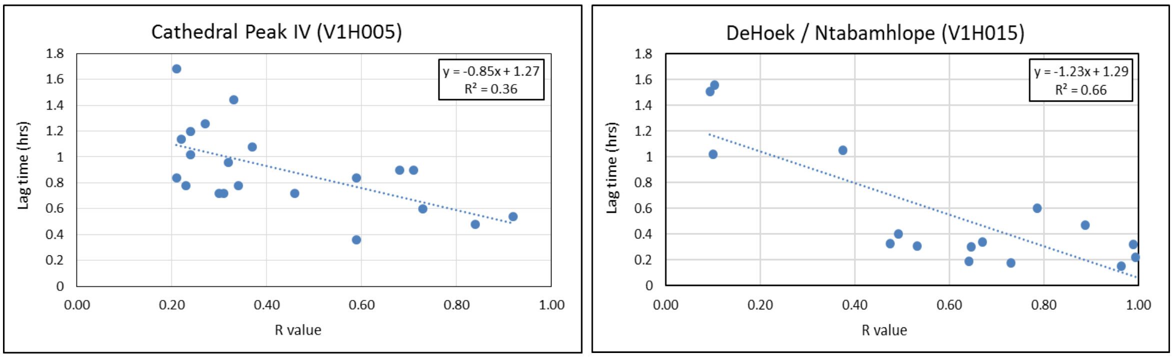

Figure 5.8 Relationship between catchment lag time and rainfall intensity

## 5.5 Conclusions and Recommendations

In this study the influence of three parameters which directly influence the simulation of the stormflow contribution to peak discharges in the *ACRU* model have been investigated for two methods of hydrograph generation. The first method, which is the default option applied in the *ACRU* model, uses the design stormflow peak discharge equation (the single UH approach), and relies on the simulated stormflow volume and estimated catchment lag time only. The second method, the incremental UH approach, also requires an estimate of both stormflow volume and catchment lag time, as well as the temporal distribution of daily rainfall, where a fixed regionalised synthetic rainfall distribution is generally assumed for application in South Africa.

The lack of reliable sub-daily rainfall data, particularly consistent and accurate short-duration rainfall data, was a significant challenge to this study. This resulted in the use of only two pilot study catchments. These catchments were selected since they were identified to have high quality data, with the short-duration rainfall stations being highly representative of the catchments. The analysis of these two catchments, however, produced consistent trends and successfully addressed the objectives of the study to: (i) investigate the simulation of the stormflow contribution to peak discharge in detail for two case study research catchments, (ii) compare the results obtained from application of the single UH approach and the incremental UH approach, (iii) compare the simulated results when estimated parameter inputs are replaced with observed data, and (iv) investigate if there is a relationship between the distribution of daily rainfall, i.e. rainfall intensity, and catchment lag time. Through these objectives the overall aim was achieved, i.e. to guide further research and identify priority components that have the most significant influence on the stormflow peak discharge computation, as summarised below.

The following conclusions based on the analysis of the results in this chapter have been drawn:

(i) Both the single and incremental UH approaches are sensitive to stormflow volume, and although the *UQFLOW OTD* is a reasonable estimate of the daily stormflow volume, it still tends to overestimate stormflow in general.

(ii) The single UH approach, which does not account for the distribution of daily rainfall, was particularly sensitive to the estimated lag time, which varies significantly from event to event.

(iii) The incremental UH approach is sensitive to both the estimated lag times and daily rainfall distributions used, which both vary significantly from event-to-event. Based on the results obtained for the two case study catchments, however, the incremental UH approach was identified to be more sensitive to the distribution of daily rainfall used.

(iv) When applying the incremental UH approach, and both the daily rainfall distribution and catchment lag time are incorrectly estimated, a compounding of the error obtained is observed.

(v) The Schmidt and Schulze (1984) lag equation was identified to provide a relatively good estimate of the average catchment response time, and although less satisfactory, the synthetic daily rainfall distributions provided a reasonable average representation of the typical rainfall distributions observed in the catchments.

(vi) The incremental UH approach provides more accurate peak discharge estimates compared to the single UH approach, i.e. both when using parameters obtained from observed events and when using estimated and synthetic information. The results are, however, much improved when using parameters derived from the observed data. This indicates the importance of accounting for the variation of daily rainfall distributions and catchment lag times on a day-to-day basis. Therefore, to improve on the results obtained from the incremental UH approach, methods to account for these variations need to be developed.

(vii) There is a relationship between catchment lag time and rainfall intensity. Consequently, if regional relationships between rainfall intensity and lag time can be developed, adjustments to lag time estimates, such as using the Schmidt and Schulze (1984) estimate, may be made based on the rainfall intensity of the event for a specific day.

(viii) Lastly, the results highlight that accurate simulations of peak discharge may be obtained when applying both the single and incremental UH approaches when accurate inputs to the equations are used, therefore, validating that the model concepts and structure are reasonable to use in practice.

Based on these results the following recommendations are made for future research:

(i) To confirm that the incremental UH approach consistently produces superior results to the single UH approach, as identified in this chapter, i.e. the performance of the single and incremental UH approaches need to be assessed for all verification catchments used in the assessment of the CSM system developed in Chapter 4.

(ii) There is also a need to perform several additional sensitivity analyses on the CSM system developed, including the performance of the CSM system when only default datasets suggested to estimate soils and land cover information are used. In addition, the sensitivity of the approach to different lag time estimates, i.e. used to simulate the stormflow contribution to peak discharge, needs to be assessed.

(iii) Owing to the greater impact on the incremental UH approach to the sub-daily temporal distribution of daily rainfall identified in this chapter, as well as the relationship identified between the daily rainfall distribution and lag time, it is recommended that methods to account for the actual distribution of daily rainfall on a day-to-day basis be prioritised in future research. This information may then be used to further improve the estimation of lag time and peak discharge on a day-to-day basis.

(iv) Linked to the previous point, further investigation of the links between rainfall intensity and catchment lag time is recommended, with the possibility of developing regionalised relationships for South Africa.

(v) Another aspect to consider, which was not applicable in this chapter, since the catchments were very small (approximately 1 km$^2$), with rain gauges located within the catchments, is the spatial distribution of rainfall. As catchment size increases the distribution of rainfall over the catchment is non-uniform and varies from event-to-event. Therefore, it is recommended that methods to account for the spatial distribution of rainfall be investigated. It is also hypothesised that lag time may change as a function of the spatial distribution of rainfall, and therefore these considerations should also be included in further research.

Chapter 6 addresses Recommendations (i) and (ii) made above.

# 6. IMPACT OF MODEL CONFIGURATION AND PARAMETER ESTIMATION ON THE PERFORMANCE OF THE CONTINUOUS SIMULATION MODELLING SYSTEM DEVELOPED AND A PROPOSAL FOR A FINAL SYSTEM

This chapter assesses the impact of model configuration and parameter estimation, i.e. using different sources of input information such as land cover and soils, on the performance of the CSM system developed and assessed in the previous chapters.

## 6.1 Introduction

In Chapter 5 the performance and sensitivity of both the SCS-based single and incremental UH approaches, as applied in the *ACRU* model, were assessed for two case study catchments with high quality rainfall and streamflow data. This included the sensitivity of each of the approaches to the respective inputs required. The single UH approach requires an estimate of the daily stormflow volume and catchment lag time, while the incremental UH approach requires both these inputs, as well as the temporal distribution of daily rainfall. A comparison between the performance of the two approaches was also performed. The results indicated that: (i) the revised fraction of simulated stormflow used in the peak discharge equation (*UQFLOW OTD*) is a reasonable estimate of the daily stormflow volume, (ii) both the single and incremental UH approaches are sensitive to lag time which varies significantly from event-to-event, the Schmidt and Schulze (1984) estimated lag time was found to be a reasonable approximation of the average catchment response time, (iii) when using the incremental UH approach the computation is sensitive to the distribution of daily rainfall used, and the simulations were more sensitive to the sub-daily distribution of daily rainfall used compared to the estimated lag time used, and (iv) it was found that the incremental UH approach, applied with all the estimated and/or synthetic inputs, performed better than the single UH approach, also applied with all the estimated inputs. Based on the results obtained a recommendation was made to assess the performance of the single and incremental UH approaches on all verification catchments used in the assessment of the CSM system in Chapter 4. A recommendation was also made to perform several additional sensitivity analyses on the CSM system developed, including the performance of the CSM system when available default datasets are used to estimate soils and land cover information, as opposed to more detailed site-specific land cover and soils information. In addition, an assessment of the sensitivity of the approach to different lag time estimates, i.e. used to simulate the stormflow contribution to peak discharge, was recommended.

Based on the above results and recommendations, the overall aim of this chapter is to assess the impact of model configuration and parameter estimation on the performance of the CSM system developed for DFE in South Africa.

The first objective of this chapter is to identify if the incremental UH approach, with the Schmidt and Schulze (1984) estimated lag and synthetic daily rainfall distributions (Weddepohl, 1988), consistently performs better than the single UH approach at other sites, i.e. all of the verification catchments used in the assessment of the CSM system in Chapter 4. Based on these results the most appropriate approach for use in the CSM system will be identified, and this approach will be selected as the default option and applied for all subsequent assessments.

The second objective of this chapter is to assess the performance of the CSM system: (i) when different sources of input information are used, such as the currently available default land cover and soils maps suggested for use with the CSM system in Chapter 3, i.e. when site-specific information is not available, and (ii) when different options to estimate catchment lag time are used. This is performed to identify the most appropriate configuration of the CSM system to recommend for DFE in South Africa. Scenarios considered include: (i) use of *ACRU* specific soils information mapped for the country (Schulze and Horan, 2008), (ii) use of national SCS-SA soil group maps developed by Schulze (2012) and Schulze and Schütte (2018), (iii) use of the National Land Cover maps of 2000 (NLC 2000) developed by the ARC and CSIR (2005), and (iv) use of the SCS lag time (SCS, 1972) and lag time estimated from the time to peak equations developed by Gericke and Smithers (2016) for selected climatic regions in South Africa.

## 6.2 Catchments used in Verification Studies

The same verification catchments used in the initial assessment of the CSM system in Chapter 4 (Figure 4.1) are used in this chapter to address the objectives defined above. The details about each of the catchments are summarised in Table 4.1 and Table 4.2 (Chapter 4), which includes site-specific information relating to land cover and soils information. Similarly, the climate information used as input to the *ACRU* model for all assessments in this chapter are constant and are identical to those documented in Table 4.3 (Chapter 4).

## 6.3 Model Performance Assessment Criteria

For all investigations and assessments of model performance the Nash–Sutcliffe Efficiency (NSE) between simulated and observed daily streamflow and/or peak discharge values is used. The NSE gives an indication of overall model performance, i.e. in terms of the full range of simulated flows, i.e. low, intermediate and high flows.

For comparison and to summarise the differences between the design values computed from the observed and simulated Annual Maximum Series (AMS) using the GEV distribution fitted to the data using L-moments (Hosking and Wallis, 1997), both the Mean Relative Error (MRE) and Mean Absolute Relative Error (MARE) were used. The MRE was calculated using Equation 4.5, and the MARE was calculated using Equation 4.6, as detailed in Chapter 4.

## 6.4 Single versus Incremental UH Approach

This section outlines the methodology applied and results obtained for Objective 1 – Identify if the incremental UH approach with the Schmidt and Schulze (1984) estimated lag and synthetic daily rainfall distributions (Weddepohl, 1988) consistently performs better than the single UH approach, also using the Schmidt and Schulze (1984) estimated lag time, for all verification catchments (Section 6.2). These include operational catchments where short duration rainfall data are not available, which is generally the case when estimating design floods in practice in South Africa, due to the scarcity of short duration sub-daily rainfall data in South Africa.

### 6.4.1 Methodology

The results obtained from the assessment of the CSM system developed, as documented in Chapter 4, i.e. with revision to the volume used in the peak discharge computation (*UQFLOW OTD*), and applying the single UH approach, are compared to those obtained when applying the incremental UH approach with the synthetic rainfall distributions (Weddepohl, 1988) applicable to each catchment, as detailed in Table 4.1. In both cases the same input information from Table 4.1 was used, and only the peak discharge computation procedure was changed.

### 6.4.2 Results and discussion

In terms of overall model performance as indicated by the NSE values for all verification catchments, as summarised in Table 6.1, it is evident that the incremental UH approach performed better than the single UH approach (higher NSE values) for nine (9) catchments and with slightly lower NSE values at V1H032 and X2H027. Catchments V1H032 and X2H027 are considerably larger than the other catchments and therefore the results may suggest that the performance of the incremental UH approach deteriorates with catchment size, i.e. for catchments outside of the recommended size range (< 50 km$^2$) defined for the *ACRU* model (Schulze, 1995). The results, however, for these two catchments are only slightly worse than those obtained from the single UH approach, whereas for the remaining catchments, in most cases, substantial improvements were obtained when using the incremental UH approach compared to the single UH approach. Therefore, in general the incremental UH approach provides better results compared to the single UH approach. The general poor performance of the model with predominantly negative NSE values, for both the single and incremental UH approaches used to simulate the peak discharge, is attributed to (i) the simulated stormflow volume on any given day not being representative of the observed stormflow volume for that day, (ii) variations in the sub-daily temporal distribution of daily rainfall from day-to-day, and (iii) variations in lag time from day-to-day, as detailed and discussed in Chapters 4 and 5. Therefore, on a day-to-day basis the simulated versus observed comparisons are relatively poor, however, the predominant or most typical conditions are accounted for. Recommendations have been made in Chapter 5 to further improve on these results and incorporate or develop methods to more adequately account for these variations on a day-to-day basis.

Table 6.1 Comparison of NSE results between observed versus simulated daily peak discharges when applying the single and incremental UH approaches

| **Catchment** | **Area ($km^2$)** | **NSE Daily Peak Discharges - Single UH approach** | **NSE Daily Peak Discharges - Incremental UH approach** |
|---|---|---|---|
| **U2H020** | 0.26 | -1.89 | -1.20 |
| **V7H003** | 0.52 | -1.12 | -0.49 |
| **G2H010** | 0.73 | -23.70 | -3.14 |
| **V1H005** | 0.98 | -10.53 | -7.47 |
| **V1H015** | 1.04 | -1.24 | -0.41 |
| **U2H018** | 1.31 | -10.02 | -5.59 |
| **W1H016** | 3.30 | -0.70 | 0.27 |
| **X2H026** | 13.82 | -6.57 | -4.68 |
| **A9H006** | 16.00 | -1.43 | -0.83 |
| **V1H032** | 67.80 | 0.17 | -0.01 |
| **X2H027** | 77.16 | -3.91 | -4.49 |

A comparison of the MRE between observed and simulated design peak discharges, for return periods ranging from 2 to 100 years, when applying both the single and incremental UH approaches is shown in Figure 6.1. The results, similar to the NSE values, indicate that improved design peak discharges are obtained for all verification catchments (lower MRE values) when using the incremental UH approach, except once again for catchments V1H032 and X2H027. The results for catchment V1H032, however, are very similar when applying the two approaches, i.e. the results are practically identical, with the single and incremental UH approach results sharing the same plotting position in Figure 6.1, and the results obtained when applying the incremental UH approach are only slightly worse for catchment X2H027 compared to when the single UH approach is applied. The MARE was not presented here since the values are identical to the MRE values, i.e. both methods consistently overestimate the observed design peak discharges. The significant differences between the results obtained for the Lambrechtsbos B (G2H010) Catchment (Figure 6.1), are related to the ability of the incremental UH approach to account for the distribution of daily rainfall. The Lambrechtsbos B (G2H010) Catchment falls into rainfall intensity Region 1 associated with low intensity rainfall uniformly distributed throughout the day. For the single UH approach the rainfall intensity is not accounted for and consequently the storm duration is assumed to be equal to the catchment response time, i.e. lag time, which for this catchment is very short resulting in significantly higher peak discharge simulations. This, once again, indicates the sensitivity of the peak discharge simulations to the distribution of daily rainfall used and the importance of adequately accounting for the distribution of daily rainfall.

Therefore, from the NSE and MRE values obtained above it may be concluded that in general the incremental UH approach provides better results, and should therefore be used as the default option in the CSM system. Consequently, the incremental UH approach will be used in all subsequent investigations and assessments in the sections to follow. In addition, there is room for more improvement in the results when using this approach, if the actual distribution of daily rainfall, or an improved method of disaggregating the daily rainfall into a hyetograph on a day-to-day basis, is developed and used. Furthermore, relationships between rainfall intensity and catchment lag time were shown in Chapter 5, therefore, lag time may possibly be adjusted based on the distribution of daily rainfall in future development of the system.

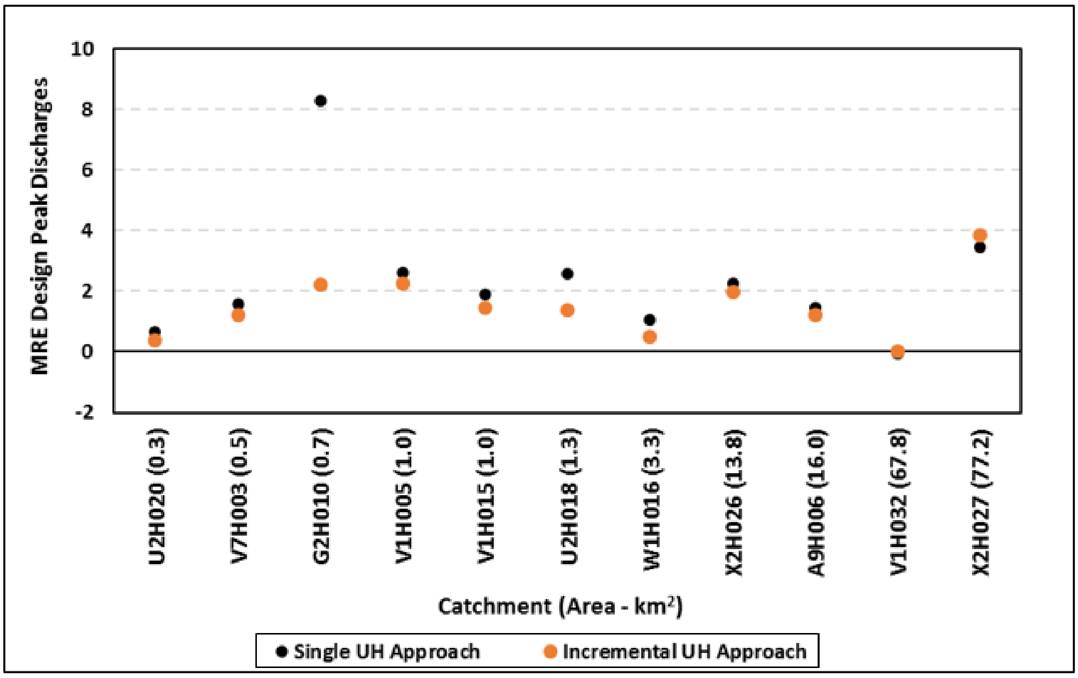

Figure 6.1 MRE between observed and simulated design peak discharges (2 – 100 year return period) when applying the single versus incremental UH approach

## 6.5 Sensitivity of the CSM System to Different Sources of Input Information

This section outlines the methodology applied and results obtained for Objective 2 – Assess the performance of the CSM system when different sources of input information are used.

### 6.5.1 Scenario investigations

To address Objective 2, several different scenarios were investigated. The different scenarios investigated are summarised in Table 6.2. All scenarios use *UQFLOW OTD* as the stormflow input to the peak discharge computation and, based on the results obtained above, all scenarios use the incremental UH approach to simulate peak discharge.

Table 6.2 Summary of different scenarios assessed

| **Scenario** | **Land Cover Information** | **SCS-SA Soil Group** | ***ACRU* Soils Inputs** | **Lag Time Estimation** |
|---|---|---|---|---|
| **Current CSM System** | Site-specific where available or NLC 2000 (Table 4.1) | Site-specific where available or Schulze (2012) (Table 4.1) | Default values assigned to SCS-SA soil groups (Rowe, 2015) (Table 3.4) | Schmidt and Schulze Lag (Table 4.1) |
| ***ACRU* National Soils** | Site-specific where available or NLC 2000 (Table 4.1) | Site-specific where available or Schulze (2012) (Table 4.1) | National soils map developed by Schulze and Horan (2008) (Table 4.2) | Schmidt and Schulze Lag (Table 4.1) |
| **Schulze 2012 SCS Soils** | Site-specific where available or NLC 2000 (Table 4.1) | Schulze (2012) (Table 6.3) | Default values assigned to SCS-SA soil groups (Rowe, 2015) (Table 3.4) | Schmidt and Schulze Lag (Table 4.1) |
| **Schulze and Schütte 2018 SCS Soils** | Site-specific where available or NLC 2000 (Table 4.1) | Schulze and Schütte (2018) (Table 6.3) | Default values assigned to SCS-SA soil groups (Rowe, 2015) (Table 3.4) | Schmidt and Schulze Lag (Table 4.1) |
| **NLC 2000** | NLC 2000 (Table 6.4) | Site-specific where available or Schulze (2012) (Table 4.1) | Default values assigned to SCS-SA soil groups (Rowe, 2015) (Table 3.4) | Schmidt and Schulze Lag (Table 4.1) |
| **SCS Lag Equation** | Site-specific where available or NLC 2000 (Table 4.1) | Site-specific where available or Schulze (2012) (Table 4.1) | Default values assigned to SCS-SA soil groups (Rowe, 2015) (Table 3.4) | SCS Lag (Table 6.5) |

The first scenario in Table 6.2, “Current CSM System”, uses the same model configuration of the CSM system developed, as documented in Chapter 4, however, applying the incremental UH approach (as applied in the previous Section). Therefore, the same input information from Table 4.1 was used to parameterise the *ACRU* model, i.e. using site-specific land cover and soils information where available. Where site-specific land cover and soils information was not available the NLC 2000 map and Schulze (2012) SCS-SA soil group map were used, as detailed in Chapter 4. The "Current CSM System" is defined as the benchmark scenario, and for each of the remaining scenarios listed in Table 6.2, one of the sources of input information from the "Current CSM System" scenario is replaced with another source of input information. The source of the input information changed for each scenario, i.e. from the "Current CSM System" scenario, is highlighted in red text in Table 6.2. A brief description of each of the scenarios is provided in the sub-sections below. This includes the information and parameters required to parameterise the *ACRU* model for each scenario, which is provided in summary tables. References to the appropriate summary tables for each scenario is also provided in Table 6.2.

#### 6.5.1.1 *ACRU* National Soils

For this scenario the default soils information assigned to each of the respective SCS-SA soil groups by Rowe (2015), detailed in Table 3.4, were replaced with those obtained for each catchment from the national soils map developed by Schulze and Horan (2008), detailed in Table 4.2. This scenario was included to assess if using national soils information would improve the results obtained from the Current CSM System scenario.

#### 6.5.1.2 Schulze 2012 SCS Soils and Schulze and Schütte 2018 SCS Soils

For these two scenarios the SCS-SA soil group, as obtained from each of the respective national SCS-SA soil group maps was changed, i.e. if different to that obtained for the Current CSM System. In each case the default *ACRU* soils information applicable to each SCS-SA soil group (Table 3.4) was used. The SCS-SA soil groups assigned to each catchment for these scenarios are presented in Table 6.3, the SCS-SA soil groups assigned in the Current CSM System are also included for comparison. In each case the SCS-SA *CN* and *QFRESP* and *SMDDEP* parameter values for each SCS-SA soil group identified are also included (Table 6.3). The *ACRU* land cover classes used are the same as those used in the Current CSM System. It can be seen from Table 6.3 that in certain cases, highlighted in yellow, the SCS-SA soil group obtained from each of the national SCS-SA soil group maps is the same as those obtained for the Current CSM System, i.e. from the literature (site-specific information). In many cases, however, the SCS-SA soil groups obtained from the national SCS-SA soil group maps are different to those obtained for the Current CSM System. Occasionally the differences are substantial. This may be attributed to the scale at which the mapping was performed and the methods used to develop the national SCS-SA soil group maps. For example, the maps generated by Schulze and Schütte (2018) were developed at the scale of terrain units and therefore capture information about soils based on their specific location within the landscape, e.g. the Crest, Scarp, Mid-slope, Foot-slope and Valley-bottom. This largely explains the relatively significant differences obtained between the two maps in certain cases. For further details regarding the mapping of SCS-SA soil groups refer to Schulze (2012) and Schulze and Schütte (2018). The results from these scenarios will indicate the impact that using default soils information has on the performance of the CSM system. In addition, the results will be used to establish which national SCS-SA soil group map should be used with the CSM system, i.e. which map generally results in the best performance.

Table 6.3 SCS-SA soil groups obtained for the Current CSM System compared to those obtained from the national SCS-SA soil group maps

| **Catchment** | **Area (km$^2$)** | **SCS-SA Soil Group Current CSM System** | ***CN*** | ***QFRESP*** | ***SMDDEP*** | **SCS-SA Soil Group Schulze 2012** | ***CN*** | ***QFRESP*** | ***SMDDEP*** | **SCS-SA Soil Group Schulze and Schütte 2018** | ***CN*** | ***QFRESP*** | ***SMDDEP*** |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Cedara (U2H020)** | 0.26 | A/B | 61 | 0.6 | 0.25 | B/C | 75 | 0.9 | 0.3 | B | 69 | 0.8 | 0.25 |
| **DeHoek / Ntabamhlope (V7H003)** | 0.52 | B/C | 75 | 0.9 | 0.25 | C | 79 | 1 | 0.3 | A/B | 61 | 0.6 | 0.25 |
| **Jonkershoek - Lambrechtsbos B (G2H010)** | 0.73 | A/B | 33 | 0.3 | 0.45 | B | 47 | 0.3 | 0.3 | C | 57 | 0.5 | 0.25 |
| **Cathedral Peak IV (V1H005)** | 0.98 | A/B | 51 | 0.4 | 0.25 | C | 74 | 0.9 | 0.3 | B/C | 68 | 0.8 | 0.25 |
| **DeHoek / Ntabamhlope (V1H015)** | 1.04 | B | 61 | 0.6 | 0.25 | C | 74 | 0.9 | 0.3 | B | 61 | 0.6 | 0.25 |
| **Cedara (U2H018)** | 1.31 | B | 47 | 0.3 | 0.26 | B/C | 52 | 0.4 | 0.3 | B | 47 | 0.3 | 0.26 |
| **Zululand (W1H016)** | 3.30 | B | 61 | 0.6 | 0.25 | B | 61 | 0.6 | 0.3 | B/C | 68 | 0.8 | 0.25 |
| **X2H026** | 13.82 | A/B | 51 | 0.4 | 0.25 | B/C | 68 | 0.7 | 0.3 | B | 62 | 0.6 | 0.25 |
| **A9H006** | 16.00 | B/C | 52 | 0.4 | 0.25 | B/C | 52 | 0.4 | 0.3 | B | 47 | 0.3 | 0.26 |
| **V1H032** | 67.80 | C | 74 | 0.9 | 0.25 | C | 74 | 0.9 | 0.3 | B | 61 | 0.6 | 0.25 |
| **X2H027** | 77.16 | A/B | 51 | 0.4 | 0.25 | B/C | 68 | 0.7 | 0.3 | B | 62 | 0.6 | 0.25 |

### 6.5.1.3 NLC 2000

For this scenario the site-specific land cover information, where available for each catchment, was replaced with land cover information obtained from the NLC 2000 maps. The NLC 2000 maps were used since they are likely to be most representative of the actual land cover during the modelling period. The land cover classes obtained for each catchment from the NLC 2000 map are summarised in Table 6.4, along with the default assigned revised SCS-SA land cover classes and associated *ACRU* land cover classes, i.e. as assigned in the development of the CSM system (Chapter 3) as detailed below, including an explanation of the highlighted cells in Table 6.4.

In many cases the land cover information obtained from the NLC 2000 maps is the same as the site-specific information in the Current CSM System, however, the hydrological condition is different. For example, from the literature reviewed it was identified that the land cover for Cathedral Peak IV (V1H005) is Unimproved (Natural) Grassland, assumed to be in good condition as it is a well preserved and protected research catchment. From the NLC 2000 map the same land cover class was identified, i.e. Unimproved (Natural) Grassland. When developing the CSM system (Chapter 3), however, a single default SCS-SA land cover class from the revised SCS-SA land cover classification had to be assigned to each land cover class in the NLC 2000 classification. To be conservative and rather over-estimate design values an intermediate hydrological condition class was assumed, in this case Unimproved (Natural) Grassland in fair condition. In the NLC 2000 classification there is also a Degraded Unimproved (Natural) Grassland class, to which Unimproved (Natural) Grassland in poor condition from the revised SCS-SA classification was assigned. Therefore, in many cases the land cover class for this scenario simply changed from good condition (or a lower stormflow potential class) to fair condition (or a higher stormflow potential class), due to how the revised SCS-SA classes were assigned to the NLC 2000 classes by default. The user, however, may change the class if more detailed site-specific information is available. In Table 6.4, if only the hydrological condition changed, i.e. from that of the Current CSM System, the information for the catchment is highlighted in yellow if, however, the actual land cover information changed the information for the catchment is highlighted in green, and left unhighlighted if there is no change.

Table 6.4 Land cover information obtained from the NLC 2000 map and default assigned revised SCS-SA land cover classes and associated *ACRU* land cover classes

| Catchments | Area (km$^2$) | NLC2000 Classes | Revised SCS-SA Land Cover Class | Treatment / Class Type | Hydrological Condition | *ACRU* Land Cover Class Assigned to Revised SCS-SA Class (COMPOVEG Number / Source) | SCS-SA Soil Group Literature | *CN* | *QFRESP* (QF) | *SMDDEP* (SM) |
|---|---|---|---|---|---|---|---|---|---|---|
| **Cedara (U2H020)** | 0.26 | 3 - Thicket, Bushland, Bush Clumps, High Fynbos | Thicket, Bushland, Bush Clumps, High Fynbos | 2 = in fair condition | Fair | THICKET AND BUSHLAND etc (5030101) | A/B | 49 | 0.32 | 0.25 |
| **DeHoek / Ntabamhlope (V7H003)** | 0.52 | 6 - Unimproved (natural) Grassland | Unimproved (Natural) Grassland | 2 = in fair condition | Fair | UNIMPROVED GRASSLAND (5060103) | B/C | 75 | 0.91 | 0.25 |
| **Jonkershoek - Lambrechtsbos B (G2H010)** | 0.73 | 3 - Thicket, Bushland, Bush Clumps, High Fynbos (18%) | Thicket, Bushland, Bush Clumps, High Fynbos | 2 = in fair condition | Fair | THICKET AND BUSHLAND etc (5030101) | A/B | 49 | 0.32 | 0.25 |
| | | 9 - Forest Plantations (Pine spp) (82%) | Forests & Plantations | Humus depth 50 - 100mm | Fair/Intermediate site prep | FOREST PLANTATIONS GENERAL (Schulze, 2013 and Clark, 2015) | | 51 | 0.37 | 0.25 |
| **Cathedral Peak IV (V1H005)** | 0.98 | 6 - Unimproved (natural) Grassland | Unimproved (Natural) Grassland | 2 = in fair condition | Fair | UNIMPROVED GRASSLAND (5060103) | A/B | 61 | 0.59 | 0.25 |
| **DeHoek / Ntabamhlope (V1H015)** | 1.04 | 6 - Unimproved (natural) Grassland | Unimproved (Natural) Grassland | 2 = in fair condition | Fair | UNIMPROVED GRASSLAND (5060103) | B | 69 | 0.78 | 0.25 |
| **Cedara (U2H018)** | 1.31 | 10 - Forest Plantations (Acacia spp) & 9 - Forest Plantations (Pine spp) | Forests & Plantations | Humus depth 50 - 100mm | Fair/Intermediate site prep | FOREST PLANTATIONS GENERAL (Schulze, 2013 and Clark, 2015) | B | 62 | 0.62 | 0.25 |
| **Zululand (W1H016)** | 3.30 | 28 - Cultivated, temporary, subsistence, dryland (95%) | Row Crop (Summer rainfall zones) | 3 = Straight row + conservation tillage | Poor | MAIZE - ALL AREAS = NOV 1GROWING SEASON = 140 days Sabie (3120102) | B | 79 | 1.00 | 0.25 |
| | | 6 - Unimproved (natural) Grassland (5%) | Unimproved (Natural) Grassland | 2 = in fair condition | Fair | UNIMPROVED GRASSLAND (5060103) | | 69 | 0.78 | 0.25 |
| **X2H026** | 13.82 | 9 - Forest Plantations (Pine spp) & 1 - Forest (indigenous) (69%) | Forests & Plantations | Humus depth 50 - 100mm | Fair/Intermediate site prep | FOREST PLANTATIONS GENERAL (Schulze, 2013 and Clark, 2015) | A/B | 51 | 0.37 | 0.25 |
| | | 3 - Thicket, Bushland, Bush Clumps, High Fynbos (18%) | Thicket, Bushland, Bush Clumps, High Fynbos | 2 = in fair condition | Fair | THICKET AND BUSHLAND etc (5030101) | | 49 | 0.32 | 0.25 |
| | | 6 - Unimproved (natural) Grassland (13%) | Unimproved (Natural) Grassland | 2 = in fair condition | Fair | UNIMPROVED GRASSLAND (5060103) | | 61 | 0.59 | 0.25 |
| **A9H006** | 16.00 | 9 - Forest Plantations (Pine spp) & 8 - Forest Plantations (Eucalyptus spp) | Forests & Plantations | Humus depth 50 - 100mm | Fair/Intermediate site prep | FOREST PLANTATIONS GENERAL (Schulze, 2013 and Clark, 2015) | B/C | 67 | 0.73 | 0.25 |
| **V1H032** | 67.80 | 6 - Unimproved (natural) Grassland | Unimproved (Natural) Grassland | 2 = in fair condition | Fair | UNIMPROVED GRASSLAND (5060103) | C | 79 | 1.00 | 0.25 |
| **X2H027** | 77.16 | 9 - Forest Plantations (Pine spp) & 1 - Forest (indigenous) (87%) | Forests & Plantations | Humus depth 50 - 100mm | Fair/Intermediate site prep | FOREST PLANTATIONS GENERAL (Schulze, 2013 and Clark, 2015) | A/B | 51 | 0.37 | 0.25 |
| | | 6 - Unimproved (natural) Grassland (13%) | Unimproved (Natural) Grassland | 2 = in fair condition | Fair | UNIMPROVED GRASSLAND (5060103) | | 61 | 0.59 | 0.25 |

#### 6.5.1.4 SCS Lag Equation

For this scenario, replacement of the Schmidt and Schulze (1984) estimated lag time with the SCS lag time (SCS, 1972) is considered. Use of the lag time estimated from the time to peak equations developed by Gericke and Smithers (2016) was also investigated. However, it was excluded, as detailed below. Table 6.5 provides the lag time estimates obtained from the two approaches mentioned above, as well as those obtained from the Schmidt and Schulze (1984) equation, for comparison. For certain catchments, as indicated by N/A values, lag time estimates from the Gericke and Smithers (2016) approach could not be obtained since the catchments fall outside of the four regions for which the approach was developed. In addition, as seen in Table 6.5, the lag time estimates obtained from the Gericke and Smithers (2016) approach were significantly larger than those obtained for the other two approaches, and are often unrealistically high. This is likely due to the fact that the time to peak equations derived by Gericke and Smithers (2016) were developed for medium to large catchments (20 – 35 000 km$^2$), and therefore perform poorly on small catchments, or are not applicable to small catchments. For this reason and since lag time estimates could not be obtained for all catchments this estimate of lag time was not considered. Therefore, an assessment is only performed for the replacement of the Schmidt and Schulze (1984) estimated lag time with the SCS lag time (SCS, 1972). As indicated in Table 6.5 the SCS lag time (SCS, 1972) estimates are generally shorter than the Schmidt and Schulze (1984) lag time estimates, with the exception of Catchments G2H010, X2H026 and X2H027.

Table 6.5 Comparison of the Schmidt and Schulze (1984) estimated lag time with alternative lag time estimates

| Catchments | Area (km$^2$) | Schmidt-Schulze Lag (h) | SCS Lag (h) | Gericke Lag (h) |
|---|---|---|---|---|
| **Cedara (U2H020)** | 0.26 | 0.54 | 0.14 | 11.71 |
| **DeHoek / Ntabamhlope (V7H003)** | 0.52 | 0.47 | 0.19 | 5.54 |
| **Jonkershoek - Lambrechtsbos B (G2H010)** | 0.73 | 0.64 | 0.75 | 3.77 |
| **Cathedral Peak IV (V1H005)** | 0.98 | 0.47 | 0.39 | 11.38 |
| **DeHoek / Ntabamhlope (V1H015)** | 1.04 | 0.58 | 0.33 | 6.52 |
| **Cedara (U2H018)** | 1.31 | 0.67 | 0.50 | 5.61 |
| **Zululand (W1H016)** | 3.30 | 1.74 | 1.02 | N/A |
| **X2H026** | 13.82 | 1.11 | 1.51 | N/A |
| **A9H006** | 16.00 | 2.16 | 1.23 | 4.18 |
| **V1H032** | 67.80 | 1.71 | 1.55 | 6.42 |
| **X2H027** | 77.16 | 2.16 | 3.45 | N/A |

### 6.5.2 Methodology

The methodology applied to assess the impact of each scenario on model performance was as follows:

(i) Setup the *ACRU* model for each scenario described above and simulate daily streamflow volumes and daily peak discharges.

(ii) Calculate the NSE between observed and simulated daily streamflow volumes and peak discharges for each scenario.

(iii) Calculate the observed and simulated design daily streamflow volumes and peak discharges for each scenario, and calculate the MRE and MARE between observed and simulated design values, as described in Section 6.3.

(iv) Repeat this for all verification catchments.

(v) Calculate the average NSE, MRE and MARE values across all catchments for each scenario.

(vi) Compare and discuss the results and comment on the sensitivity of the CSM system to different sources of input information, and propose a final CSM system.

### 6.5.3 Results and discussion

Figure 6.2 summarises the average NSE values obtained for simulated versus observed Daily Streamflow Volumes (DyV) and Daily Peak Discharges (DyQp), averaged across all verification catchments, excluding Lambrechtsbos B (G2H010), for each model scenario investigated. Similarly, Figure 6.3 summarises the average MRE and MARE values obtained for simulated versus observed Design Streamflow Volumes (DnV) and Design Peak Discharges (DnQp), averaged across all verification catchments, excluding Lambrechtsbos B (G2H010). As identified in Chapter 4, the results from the Lambrechtsbos B (G2H010) Catchment were particularly poor, therefore as performed in Chapter 4 the results from this catchment were excluded from both the NSE summaries (Figure 6.2) and MRE and MARE summaries (Figure 6.3) are presented below.

In terms of the overall model performance for each scenario as summarised by the NSE values in Figure 6.2, it is evident that the Current CSM system developed produces the best results, with the highest NSE values in terms of both DyV and DyQp. A similar trend to the NSE values is reflected in the MRE/MARE values where this scenario produces the lowest values, indicating that the most accurate DnV and DnQp estimates are obtained for the Current CSM System scenario. In terms of the DnV for this scenario, the MRE is lower than the MARE, indicating a combination of both under and overestimation. In terms of the DnQp for this scenario, the MRE and MARE are the same, indicating consistent over-simulation of the DnQp values. It is important to highlight that the results varied from catchment to catchment, however, these results summarise the overall general performance of each scenario.

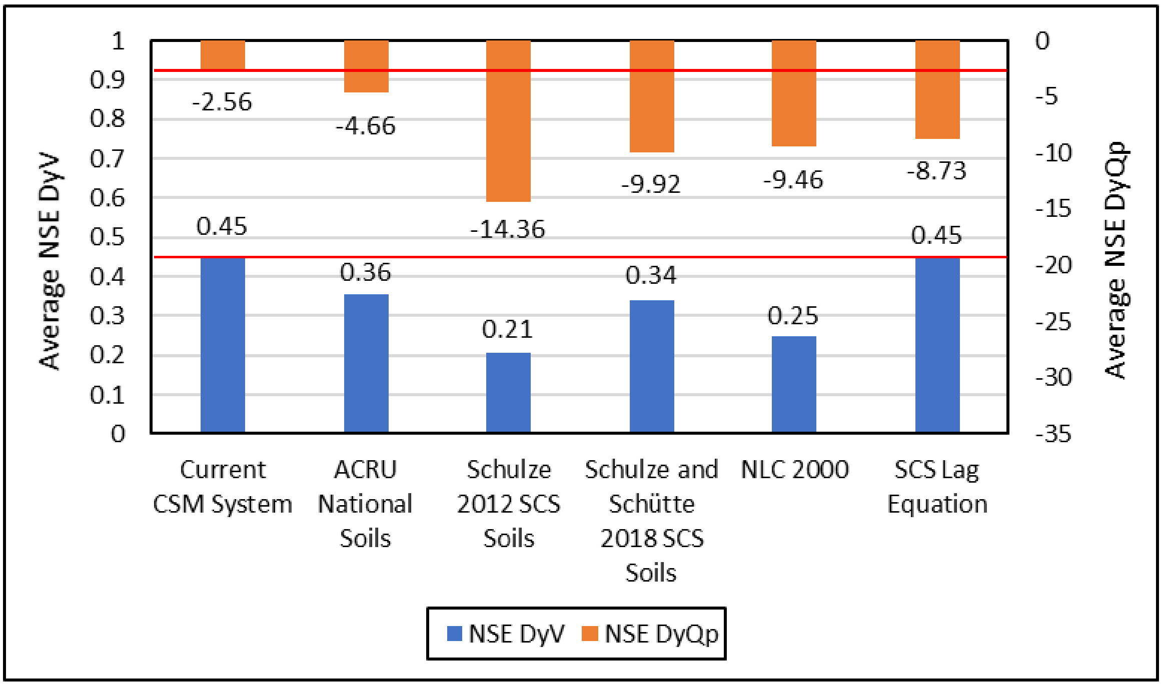

Figure 6.2 Average NSE values obtained for simulated versus observed Daily Streamflow Volumes (DyV) and Daily Peak Discharges (DyQp), averaged across all verification catchments, excluding Lambrechtsbos B (G2H010), for each model scenario

When applying the *ACRU* National Soils scenario, the results were slightly worse compared to those obtained from the Current CSM System in terms of both NSE (Figure 6.2) and MARE/MRE values (Figure 6.3). Therefore, when using the CSM system it is better to use the default soils information assigned to the selected SCS-SA soil group, as defined in the rules developed by Rowe (2015) and Rowe *et al.* (2018), and not the soils information obtained from the most updated national soils map (Schulze and Horan, 2008). This makes sense since the rules developed by Rowe (2015) and Rowe *et al.* (2018), and incorporated into the CSM System, are based on calibrations performed using this default soils information.

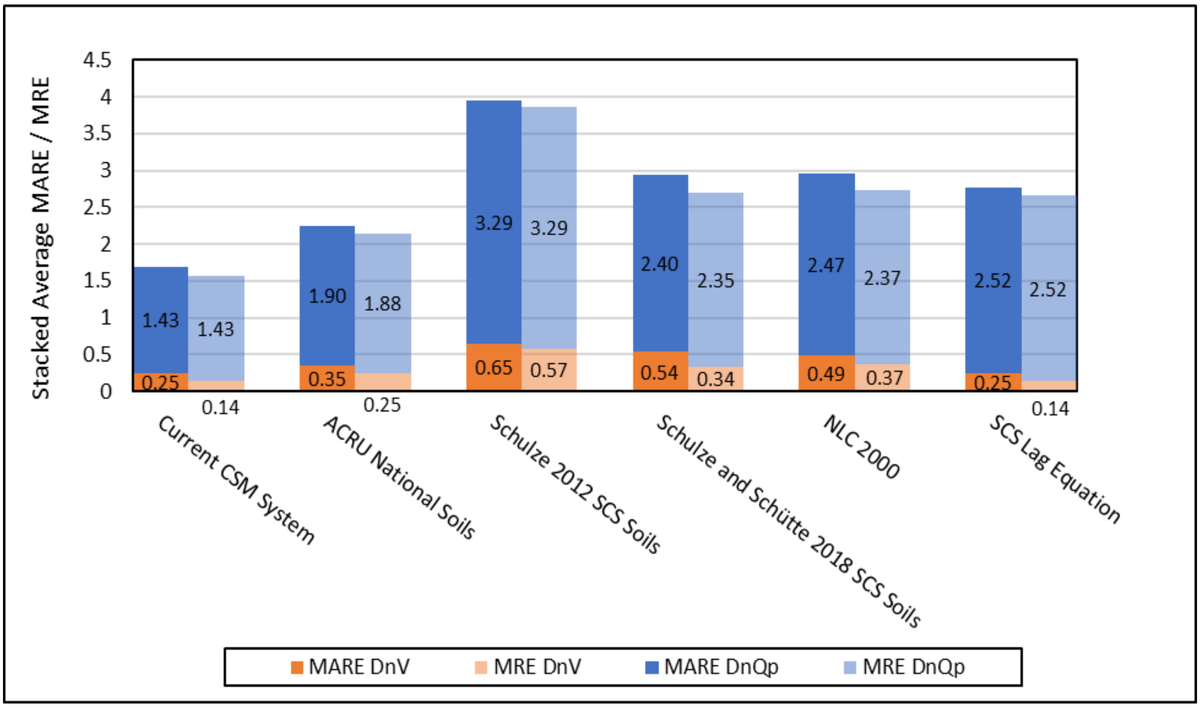

Figure 6.3 Average MARE/MRE values obtained for simulated versus observed Design Streamflow Volumes (DnV) and Design Peak Discharges (DnQp), averaged across all verification catchments, excluding Lambrechtsbos B (G2H010), for each model scenario

It is important to highlight at this stage that changes in simulated streamflow volumes have a significant influence on the simulated peak discharges, as documented in Chapters 4 and 5, i.e. since the simulated peak discharges in the model are directly dependent on the simulated streamflow volumes. This is particularly evident in both the NSE and MARE/MRE results for the scenarios where default SCS-SA soil group information is used, i.e. Schulze 2012 SCS Soils and Schulze and Schütte 2018 SCS Soils. For example, for relatively small changes in NSE values in terms of DyV there are significant changes in the corresponding DyQp NSE values. The same trend is seen when comparing the DnV MARE/MRE values to the DnQp MARE/MRE values. The results from these two scenarios in terms of both the NSE (Figure 6.2) and MARE/MRE values (Figure 6.3), and particularly in terms of the DyQp and DnQp values, are significantly worse compared to those obtained for the Current CSM System scenario. The Schulze and Schütte 2018 SCS Soils scenario performs substantially better than the Schulze 2012 SCS Soils scenario, however, in general both scenarios performed poorly. This indicates the sensitivity of the CSM system to the SCS-SA soil group selected, and inherently the sensitivity of the SCS *CN* approach, i.e. since the *ACRU* model was parameterised based on the SCS-SA *CN*s. Therefore, the results indicate that, in general, if the SCS-SA soil group is not correctly determined for use with the CSM system poor results may be obtained, with over-simulation of DnV and particularly significant over-simulation of DnQp. This highlights the importance of accurately estimating the SCS-SA soil group for a catchment, when applying the CSM system. Furthermore, since the CSM System was calibrated against SCS-SA *CNs*, this warning is also directly transferable to the SCS-SA model. Ultimately, the results indicate that the national soils maps poorly represent the actual SCS-SA soil group information at such localised scales, i.e. the national soils maps cannot capture the site-specific soils information for such small catchments. Therefore, further work on, or refinement of, the national SCS-SA soil maps is required. Based on the sensitivity of the results to the SCS-SA soil group selected, another possible consideration is that the changes in *CN* for each SCS-SA soil group are too sensitive and abrupt, and that the *CN*s for SCS-SA soil groups and land cover classes possibly need to be recalibrated for South African conditions, realising that the *CNs* were adopted from the SCS (1956) classification developed in the United States many years ago. In addition, in many cases *CN* values were simply interpolated between and extrapolated beyond other values, with very limited verification of the *CN* values being performed in South Africa, prior to this study. That being said, however, the SCS *CN*s were derived using observed data, it is therefore possible that such changes in stormflow response for corresponding changes in SCS-SA soil groups are indeed correct. This, however, can only be verified through further research, using observed data from catchments with specific land cover and soil combinations.

In terms of the NLC 2000 scenario, the NSE (Figure 6.2) and MARE/MRE (Figure 6.3) values were similar to those obtained for the Schulze and Schütte 2018 SCS Soils scenario. In terms of the NSE values, however, the NLC 2000 scenario produced a DyV NSE value substantially lower than that obtained for the Schulze and Schütte 2018 SCS Soils scenario, the DyQp NSE values, however, were very similar with the NLC 2000 NSE value being only slightly higher than that of the Schulze and Schütte 2018 SCS Soils scenario. The MARE/MRE values between the two scenarios were very similar in terms of both the DnV and DnQp. The overall error (MARE) was slightly lower for the NLC 2000 scenario, however, with a greater tendency to overestimate design values, i.e. with a slightly higher MRE value compared to the Schulze and Schütte 2018 SCS Soils scenario. For this reason, both the MARE and MRE in terms of DnQp values were slightly higher for the NLC 2000 scenario. The results for the NLC 2000 scenario therefore indicate that the CSM system is also sensitive to the land cover information used and the consequent land cover class selected. Similar to the use of default soils information, the use of default land cover maps and assigned land cover classes did not produce particularly good results, i.e. compared to those obtained from the Current CSM System. A degree of conservatism, however, was incorporated into the default land cover maps, as detailed in Section 6.5.1.3, which explains the deterioration in the results. This, similar to the results obtained from using national soils maps, indicates the importance of accurately estimating the actual land cover class for the catchment. In addition, based on the sensitivity of the results to the land cover class selected, the results, once again, possibly suggest that the changes in *CN* for each land cover class are too sensitive and abrupt, and that the *CN*s possibly need to be recalibrated for South Africa. Since the SCS *CN*s were derived using observed data it is, however, possible that such changes in stormflow response for corresponding changes in land cover classes and/or conditions are indeed correct. Once again, this can only be verified through further research, using observed data from catchments with specific land cover and soil combinations.

The final scenario assessed, was the SCS Lag Equation scenario. Since the lag equation only influences peak discharges, the NSE and MARE/MRE values, in terms of DyV and DnV respectively, are identical to those obtained for the Current CSM System scenario. In terms of the DyQp NSE and DnQp MARE/MRE values, however, the results are significantly worse for the SCS Lag Equation scenario. Therefore, for small catchments the Schmidt and Schulze (1984) lag equation produces better results. The results also, once again, indicate the sensitivity of the *ACRU* peak discharge computation to lag time estimates.

## 6.6 Conclusions and Recommendations

The aim of this chapter was to assess the impact of model configuration and parameter estimation on the performance of the CSM system developed and assessed in Chapters 3, 4 and 5. This was achieved in two successive steps, split into Objectives 1 and 2.

The first objective was to identify if the incremental UH approach with the Schmidt and Schulze (1984) estimated lag and synthetic daily rainfall distributions (Weddepohl, 1988) consistently performs better than the single UH approach, also using the Schmidt and Schulze (1984) estimated lag time, for all verification catchments used in the assessment of the CSM system in

Chapter 4. The results indicated that the incremental UH approach generally performs substantially better than the single UH approach, or at least very similarly to the single UH approach, and should therefore be used as the default peak discharge computation procedure in the CSM system. Consequently, the incremental UH approach was applied in all subsequent assessments performed in Objective 2.

The second objective of this Chapter was to use the results obtained from Objective 1, referred to as the "Current CSM System" scenario (i.e. applying the incremental UH approach, site-specific land cover and soils information and the Schmidt and Schulze (1984) estimated lag time), and compare them to those obtained for several additional scenarios where different sources of input information are used. This included the default land cover and soils maps suggested for use with the CSM system in Chapter 3, i.e. when site-specific information is not available, as well as different options to estimate catchment lag time. The results indicated that:

(i) The Current CSM system, i.e. with site-specific land cover and soils information and the Schmidt and Schulze (1984) estimated lag time produced the best results.

(ii) When applying the *ACRU* National Soils scenario, i.e. where *ACRU* specific soils information was obtained from the most updated national soils map (Schulze and Horan, 2008), the results were slightly worse compared to those obtained from the Current CSM System, i.e. where default *ACRU* specific soils information has been assigned to SCS-SA soil groups. Therefore, when using the CSM system this default soils information must be used.

(iii) The results from the Schulze 2012 SCS Soils and Schulze and Schütte 2018 SCS Soils scenarios, where SCS-SA soil groups were estimated from national maps, were significantly worse compared to those obtained for the Current CSM System scenario. The Schulze and Schütte 2018 SCS Soils scenario performed substantially better than the Schulze 2012 scenario overall. In general, however, both scenarios performed poorly. Ultimately the results indicate that the national soils maps poorly represent the actual SCS-SA soil group information at such localised scales. Therefore, further work on, or refinement of, the national SCS-SA soil group maps is required.

(iv) The NLC 2000 scenario also performed relatively poorly. A degree of conservatism, however, to rather overestimate daily and design values, was incorporated into the default land cover maps used for this scenario, which explains the deterioration in the results.

(v) The Schmidt and Schulze (1984) lag equation produced substantially better results compared to the SCS lag (1972) equation and must therefore be used to estimate lag time in the CSM system.

Based on the results obtained, as summarised above, the following final configuration for the CSM system has been proposed:

(i) The incremental UH approach is to be applied with the CSM system as the default option to simulate peak discharges.

(ii) Site-specific information related to land cover and soils should be used in preference to the national land cover and soils maps, where available. If the national soils maps are used, the Schulze and Schütte 2018 SCS Soils map must be used to estimate the SCS-SA soil group. When using NLC maps, validation of the land cover classes should be performed using globally available imagery such as Google Earth, or other means, to identify the most accurate land cover class for the catchment of interest.

(iii) The Schmidt and Schulze (1984) lag equation should be used as the default lag equation in the CSM system.

In addition to the results summarised above, it was noted that the CSM system is particularly sensitive to the land cover classes and SCS-SA soil groups selected. Therefore, an additional consideration for future research is to recalibrate or further verify the *CN*s for South Africa in order to verify that the changes in *CN* and consequent stormflow response, for changes in SCS-SA soil groups and land cover classes, are correct. As stated in Chapter 3, however, this will be challenging since there are very limited, if any, research catchment data to cover the wide range of soils and land cover combinations possible. In addition, mixes of land cover and soils classes in larger catchments, i.e. beyond the research catchments scale into the operational catchment scale, may further complicate the configuration. Further investigation of this, however, is recommended in future research.

In conclusion, although the results when using the default soils and land cover inputs were not particularly good, the CSM system provides a consistent and conceptually sound approach to estimate changes in streamflow response for different land cover and soils conditions. It is acknowledged that the CSM system has relied heavily on the SCS-SA land cover classification, and in the absence of observed data, the assumption has been made that the hydrological responses from the SCS-SA model for these soils and land cover classes are reasonable. Consequently, it is possible that the *ACRU* CSM system and event-based SCS-SA model may provide similar results. Therefore, an assessment of how the results from the CSM system developed compare to those obtained from the SCS-SA model is needed. Consequently, the next chapter will compare the performance of the Current CSM System, i.e. which provided the best results in this chapter, to the results from the SCS-SA model using the same input information. It is however, hypothesised that the CSM system will perform better since the approach accounts for the antecedent soil water conditions before each event and considers both stormflow and interflow/baseflow, none of which the SCS-SA model accounts for.

# 7. A COMPARATIVE PERFORMANCE ASSESSMENT BETWEEN THE FINAL CONTINUOUS SIMULATION MODELLING SYSTEM PROPOSED AND THE TRADITIONAL SCS-SA MODEL

This chapter contains a comparison of the performance of the final CSM system proposed above to the performance of the traditional SCS-SA model and associated antecedent soil water adjustment procedures.

## 7.1 Introduction

In the previous chapter a final CSM system for DFE in South Africa using the *ACRU* model (Schulze, 1995) was proposed. In the absence of observed data, the development of the method relies extensively on the SCS-SA land cover classification, i.e. in terms of representing hydrological responses from specific combinations of soil types, land cover classes, land cover conditions and land management practices. Consequently, the *ACRU* CSM system has been modified to use the SCS-SA land cover classification. In addition, there are striking similarities between the stormflow and peak discharge modules of the *ACRU* and SCS-SA models; hence there is a need to compare the performance of the two models for DFE. This is essential in order to identify if the *ACRU* CSM system provides better DFE estimates compared to the traditional SCS-SA model and, if so, justifies further development and implementation of the *ACRU* CSM system. It also provides the opportunity to assess the performance of the SCS-SA model when applying the initial catchment Curve Number (*CN-II*), the Median Condition Method (MCM) and the Joint Association Method (JAM).

Therefore, the objective of this chapter is to compare the performance of the final CSM system proposed in Chapter 6 to the performance of the traditional SCS-SA model when the same input information is used.

## 7.2 A Brief Overview of the *ACRU* and SCS-SA Models

At the onset it is again important to emphasise that the *ACRU* model is a daily timestep Continuous Simulation (CS) model and the SCS-SA model is an event-based model. This section provides a brief overview of each model and explains how design flood estimates are determined in each case.

In the *ACRU* model historical time series of observed daily rainfall and additional climate data, such as temperature or A-pan evaporation, are input to the model together with soils and land cover information to simulate streamflow on a daily basis. Streamflow in the model comprises of both stormflow (surface runoff) and interflow/baseflow. The soil water budgeting routines of the *ACRU* model explicitly account for antecedent soil water conditions on a daily basis. Rainfall adds water to the soil water store and evapotranspiration depletes water from the soil water store. The antecedent soil water content directly influences the simulated daily streamflow response, e.g. if a rainfall event on a particular day is preceded by another rainfall event on the previous day, and with that amount of rainfall exceeding the amount of evapotranspiration, the streamflow response on the day will be higher than that of the previous day since the soil water store is closer to full capacity and therefore more streamflow is generated. To estimate design streamflow volumes and design peak discharges, the AMS are extracted from the simulated daily values and an extreme value distribution is fitted to the AMS to estimate the design values. Further details on the computation of streamflow and peak discharge in the *ACRU* model are provided in the previous chapters.

The SCS-SA model, adapted for South African conditions by, *inter alia*, Schulze and Arnold (1979), Schmidt and Schulze (1987a) and Schmidt and Schulze (1987b), from the SCS model developed by the Soil Conservation Service of the United States of America (SCS, 1956), is a deterministic event-based model that converts a design rainfall depth into a design stormflow volume (assumed to be surface runoff volume only) and a peak discharge estimate. In the most basic implementation of the SCS-SA model, the stormflow response is simulated based on a single fixed parameter representative of the average catchment stormflow response characteristics, i.e. the initial catchment Curve Number (*CN-II*; Schmidt and Schulze, 1987a). Therefore, antecedent soil water conditions are not initially accounted for. For South Africa, two approaches were subsequently developed to adjust *CN-II* to account for antecedent soil water conditions, namely the Median Condition Method (MCM) and the Joint Association Method (JAM). The MCM is used to adjust initial *CN*s, i.e. derived from soil properties and land cover / 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, and in the SCS-SA model this water balance was computed for a 30 day period leading up to the five largest independent rainfall events from each year. 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 MCM, the 50th percentile (median) change in soil water is used to adjust *CN-II* 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 JAM, on the other hand, performs a frequency analysis on the simulated flows from the five largest 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.

It is important to note that for both the basic implementation of the SCS-SA model with *CN-II*, i.e. no antecedent soil water adjustment, as well as for the MCM, there are several options available to estimate design rainfall. These include: (i) by rainfall station search, (ii) from the hydrological response zone's representative station, (iii) user entered values for selected return periods, and (iv) design rainfall estimated using a regional, scale invariance approach (Smithers and Schulze, 2002). Refer to Schulze *et al.* (2004) for further details relating to each approach. In the development of the MCM and JAM, however, the change in soil water used to adjust *CN-II* was calculated using rainfall data from the hydrological response zone's representative station. Since the methods were developed prior to 1987 the rainfall records were relatively short, approximately 20 years (Schulze *et al.*, 2004). Therefore, when applying the MCM any of the four options listed above may be used to estimate design rainfall, however, the *CN* adjustment of *CN-II* is based on the median (50th percentile) soil water change calculated for a specific land cover and soil combination using the rainfall data from the hydrological response zone's representative station. When applying the JAM, the user does not have an option as to which method to use to estimate design rainfall, since the method does not use design rainfall estimates. This is because a frequency analysis was performed on the simulated stormflow volumes, as obtained from the five largest rainfall events in each year of record, i.e. for the length of record available for the hydrological response zone's representative station. In each case the actual soil water change prior to each event was used to adjust *CN-II* to a final curve number which is used to calculate the stormflow response to design rainfall. The 50th, 80th, 90th and 95th non-exceedance percentiles, which correspond to the 2, 5, 10 and 20 year return periods, were recorded and the results stored in summary tables for each homogeneous zone for a range of *CN-II* values representing each soil and land cover combination simulated (Schmidt and Schulze, 1987a; Schmidt *et al.*, 1987). The non-exceedance percentiles are specific to the rainfall records used in the development of the JAM and are not directly comparable to results obtained from design rainfall estimates derived from other sources, i.e. which may use different rainfall stations and have different record lengths. In addition, the return period stormflow values calculated from non-exceedance probabilities are not equivalent to return period stormflow values calculated from design rainfall estimates, i.e. as obtained from an extreme value distribution fitted to the AMS of daily rainfall. Therefore, particularly for the higher return periods, i.e. the 20-year return period, large increases in the stormflow volume and peak discharge quantiles occur when using the JAM compared to when the MCM or *CN-II* is used (Schmidt and Schulze, 1987a). Examples of this are provided in the results section of this chapter. Therefore, as recommended by Schmidt and Schulze (1987a), the JAM should be used for lower return period events (2 – 10 years), and the results for these lower return periods may be compared to those obtained from the MCM method, to identify if possibly the 20th or 80th percentile antecedent soil water change should be used to adjust *CN-II*, instead of the median (50th percentile).

## 7.3 Verification Catchments

The same verification catchments used in the previous assessments of the CSM system in Chapters 4 and 6 are used in this chapter. The locality of the verification catchments is provided in Figure 4.1. The information required to model each of the catchments is summarised in Table 4.1 and includes site-specific information relating to land cover and soils. The climate information used to drive the *ACRU* model for all assessments in this chapter are fixed and are identical to those documented in Table 4.3.

## 7.4 Methodology

This section outlines the methodology applied in this chapter. The first step was to set up both the *ACRU* and SCS-SA models.

In terms of the *ACRU* model, the same setup as used in the final CSM system proposed in Chapter 6 was used. This includes all the input information summarised in Table 4.1, and climate data listed in Table 4.3. This information was used to simulate continuous time-series of daily simulated streamflow volumes and peak discharges. The Annual Maximum Series (AMS) was then extracted from each time-series, and the Generalised Extreme Value (GEV) distribution was fitted to the AMS using L-moments (Hosking and Wallis, 1997) in order to estimate design values.

When setting up the SCS-SA model (Schulze *et al.*, 2004) the same input information summarised in Table 4.1 was used to determine the *CN*, whereas for the *ACRU* model the *QFRESP* and *SMDDEP* parameter values were used which were derived from the SCS-SA *CN*s based on the rules developed by Rowe *et al.* (2018). In terms of the SCS-SA model, design rainfall values are required as input to the model, with the exception of the JAM, as explained in Section 7.2, and not daily rainfall values. For consistency and to make the comparisons between the two models valid, the AMS from the daily rainfall file used in the *ACRU* model for each catchment was extracted, and the GEV distribution, using L-moments (Hosking and Wallis, 1997), fitted to the AMS to estimate the 1-day design rainfall values for each catchment, which were used as input to the SCS-SA model when applying *CN-II* and when applying the MCM. Therefore, in these two cases, user-entered design rainfall values were used to simulate corresponding design stormflow volumes and peak discharges. As explained in Section 7.2, the SCS-SA JAM provides results obtained from a frequency analysis performed on simulated values estimated using the hydrological response zone's representative rainfall station.

In terms of both models the Schmidt and Schulze (1984) lag equation and the incremental UH approach (Schulze, 1995) were used with the synthetic rainfall distributions identified for each catchment (Table 4.1), as defined by Weddepohl (1988). The difference was again that the peak discharges were simulated on a daily basis in the *ACRU* model and an extreme value analysis was performed to determine the design values, whereas for the SCS-SA model, with the exception of the JAM, the design stormflow volumes simulated were used to simulate design peak discharges. In the case of the JAM, however, simulated stormflow volumes at specific non-exceedance percentiles were used to simulate corresponding peak discharges.

For selected catchments graphical plots of the observed versus simulated design values are presented to visualise the typical trends in the results obtained. For comparison and to summarise the differences between the observed and simulated design values, however, both the Mean Relative Error (MRE), Equation 4.5, and the Mean Absolute Relative Error (MARE), Equation 4.6, are used, i.e. averaged across all return periods from 2 – 100 years.

The average MRE and MARE, averaged across all verification catchments for each model simulation, i.e. the final *ACRU* CSM system, the SCS-SA model with *CN-II*, the SCS-SA model applying the MCM, and the SCS-SA model applying the JAM, was then used to assess the overall performance of both models. It is important to note at this stage that below a *CN-II* value of 50 no adjustment to the *CN* is made when applying the MCM in the Visual SCS-SA model program (Schulze *et al.*, 2004). In addition, no results are available for the JAM for *CN-II* values below 50. The Windows-based Visual SCS-SA model program is an updated version of the PC DOS-based software package, SCS-SA, developed by Smithers, Schmidt, Schulze, Petersen and Lynch in 1992 (Schulze *et al.*, 2004). The software packages were developed for users, i.e. consultants and government organisations, to easily implement the SCS-SA model approach, as documented by Schmidt and Schulze (1987a). The Windows-based Visual SCS-SA software is the most widely applied implementation of the SCS-SA model in South Africa and was therefore used in this study. The results from the MCM for *CN-II* values below 50 were used as obtained from the Visual SCS-SA software, i.e. unadjusted, as this is the result that would be obtained in a real-life application of the approach with this software. Only two catchments had *CN-II* values below 50 (Table 4.1) and for such low *CN*s the impact of antecedent soil water changes is small, therefore the impact on the results for the MCM is considered negligible. For the JAM the average MRE and MARE was calculated for the 9 catchments for which results were available.

## 7.5 Results and Discussion

Figure 7.1 shows the *ACRU* and SCS-SA simulation results obtained for two catchments, namely Cathedral Peak IV (V1H005) and DeHoek/Ntabamhlope (V7H003), and compares them to the observed data. These two catchments were selected to graphically depict the typical results obtained. The two catchments also have significantly different stormflow responses as indicated by the *CN*s and *QFRESP* parameter values in Table 4.1. Graphical plots, similar to those presented in Figure 7.1, for the remaining verification catchments are provided in Appendix G (Chapter 16). It is important to emphasise that the *ACRU* model simulates total streamflow which includes both stormflow and interflow/baseflow. The SCS-SA model, on the other hand, simulates only stormflow. Both models, however, use simulated stormflow to simulate the stormflow contribution to peak discharge. In the *ACRU* model the baseflow/interflow volume is uniformly distributed throughout the day and converted into a constant flow rate which is added to the simulated stormflow peak discharge. This contribution to the peak discharge, however, is negligible, particularly for design events.

For catchment V1H005 (Figure 7.1), the simulated design stormflow volumes from the SCS-SA model for *CN-II* and the MCM are very similar, since the median (50th percentile) change in soil water for this catchment is effectively zero, therefore the adjustment to *CN-II* is insignificant and the *CN-II* value is retained for the MCM. The simulated design streamflow volumes from the *ACRU* model and simulated design stormflow volumes from the SCS-SA model for *CN-II* and the MCM are considerably different for catchment V1H005 (Figure 7.1). These results indicate the importance of accounting for interflow/baseflow in terms of reproducing observed streamflow volumes correctly. This is particularly relevant to catchments such as catchment V1H005, which has highly permeable soils with high infiltration rates, dense vegetation and a low stormflow potential, as indicated by the low *CN* and *QFRESP* parameter values for this catchment (Table 4.1). For this catchment interflow/baseflow contributes significantly to the design streamflow values simulated by the *ACRU* model, i.e. when plotting only the simulated stormflow volume from the *ACRU* model the plot produces results very similar to the SCS-SA model for *CN-II* and the MCM (Figure 7.1). Therefore, since the SCS-SA model only simulates stormflow, a significant portion of the total streamflow is not accounted for, which is a limitation of the SCS-SA model. Consequently, for catchments such as catchment V1H005, the simulated stormflow from the SCS-SA model is a relatively poor approximation of the observed streamflow. For catchments such as catchment V7H003, however, which has less permeable soils with lower infiltration rates, less dense vegetation and a higher stormflow potential, as indicated by the higher *CN* and *QFRESP* parameter values in Table 4.1, the simulated stormflow volumes from the SCS-SA model are more comparable to the simulated streamflow volumes from the *ACRU* model. This is because stormflow dominates over interflow/baseflow for catchments such as catchment V7H003, and therefore the simulated stormflow is a closer approximation of the observed streamflow.

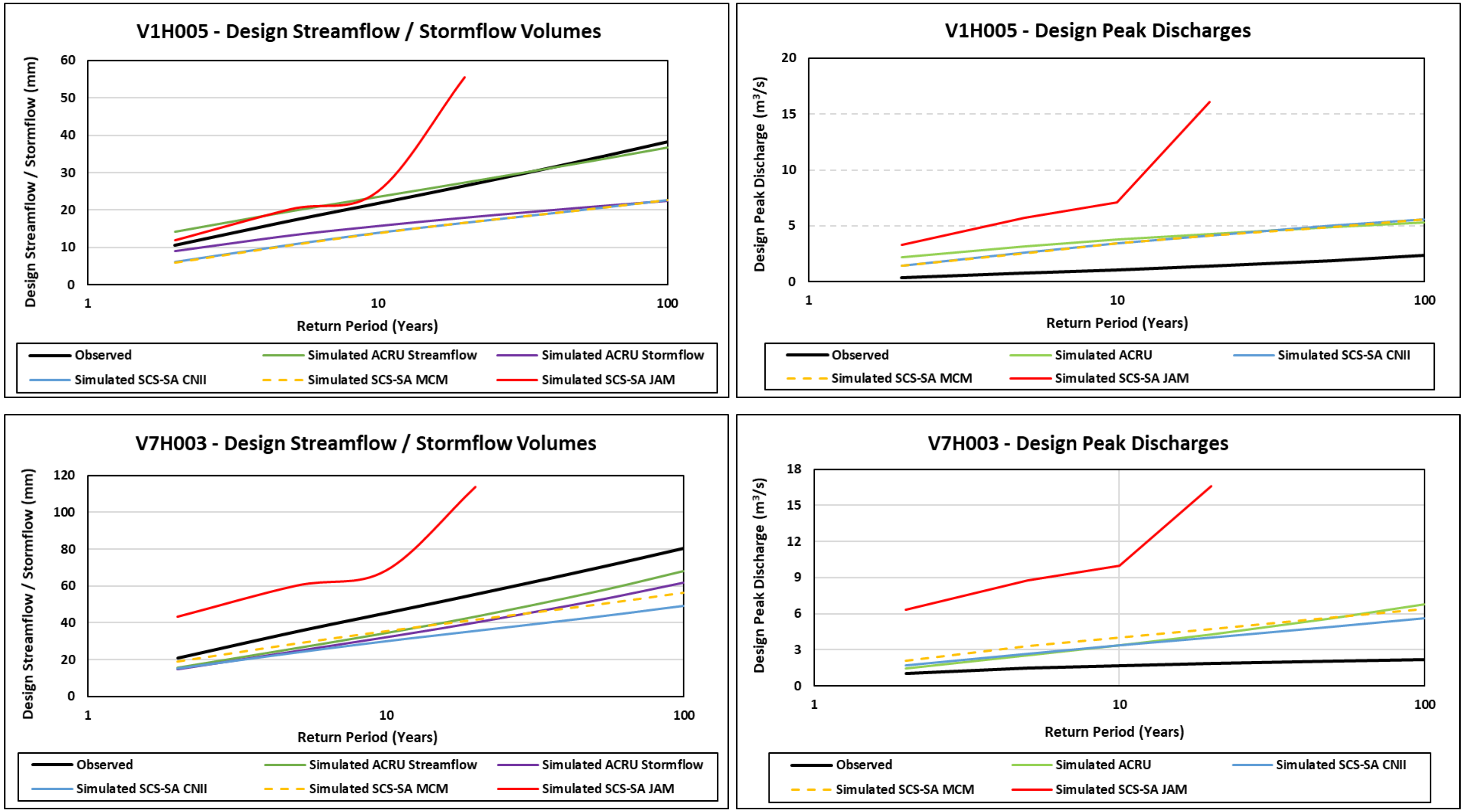

Figure 7.1 Observed and simulated design streamflow/stormflow volumes and design peak discharges for Cathedral Peak IV (V1H005) and DeHoek/Ntabamhlope (V7H003), applying both the *ACRU* and SCS-SA models

It should be noted, however, that the ability of the *ACRU* model to explicitly account for antecedent soil water also contributes to the differences observed between the design streamflow volumes simulated by the *ACRU* model and the design stormflow volumes simulated by the SCS-SA model. For catchment V7H003, the results from the SCS-SA model for the MCM are slightly better than the results from the SCS-SA model for *CN-II*.

In summary, since the SCS-SA model does not account for interflow/baseflow, the model underestimates design streamflow volumes. This highlights the advantage of using the *ACRU* CSM system over the SCS-SA model. This is supported by the results presented in Figure 7.1, where the *ACRU* model produces results most similar to the observed data, i.e. across the entire range of design values from 2 – 100 years. In terms of the design peak discharges very slight differences between the results simulated by the *ACRU* model and those simulated by the SCS-SA model for *CN-II* and the MCM were observed (Figure 7.1). This was expected since both the *ACRU* and SCS-SA models use simulated stormflow to simulate the stormflow contribution to peak discharge, and the simulated stormflow volumes from both models are very similar since the *ACRU* stormflow response was calibrated based on the SCS-SA stormflow response. The similarity in the peak discharge results suggests that antecedent soil water has a limited influence on the simulated stormflow volumes from both models, and since these differences are small there are small differences in the resulting simulated peak discharges. This further emphasises the significance that interflow/baseflow has on the total simulated streamflow, i.e. the differences in simulated stormflow volumes from the SCS-SA model and streamflow volumes from the *ACRU* model are predominantly due to the fact that a significant fraction of the simulated streamflow in the *ACRU* model comprises of interflow/baseflow.

Ultimately, both models provide reasonable estimates of the design peak discharges, however, there is a consistent over-simulation. This has been attributed to variations in daily stormflow responses, catchment lag time and rainfall intensity, all of which are approximated with estimates of average or typical conditions. Further room for improvement, particularly with the *ACRU* model, has been documented to account for these variations on a daily basis. With the SCS-SA design event-based approach only typical conditions or ensembles of possible scenarios can be simulated for design events, without the ability to replicate the actual conditions prior to each design event. The use of ensemble events or Monte Carlo simulations, however, with event-based models such as the SCS-SA model has large potential and is an approach that has received increasing attention in recent years (Kjeldsen *et al.*, 2010; Blöschl *et al.*, 2013; Ball *et al.*, 2016). This provides uncertainty bands and estimations of worst-case scenarios which provides more information to the design engineer to make more informed decisions. The SCS-SA model, however, does not account for the interflow/baseflow contribution to total streamflow which is a limitation of the approach.

Although not directly comparable, for the reasons stated in Section 7.2, the results from the SCS-SA JAM for both catchments are generally poor in terms of both the design stormflow volumes and design peak discharges. The results are more reasonable for return periods from 2 – 10 years. For the 20-year return period, however, there is a substantial increase in the quantiles, due to a frequency analysis being performed on simulated flows from a relatively short record (approximately 20 years), as explained in Section 7.2. In general, however, there is a significant overestimation of design values for these two catchments when applying the JAM.

The overall performance of the *ACRU* CSM system and the SCS-SA model for all verification catchments, excluding the Lambrechtsbos B (G2H010) Catchment, is summarised in Figure 7.2. For consistency, as performed in Chapters 4 and 6, the results from the Lambrechtsbos B (G2H010) Catchment were excluded, due to challenges associated with modelling this catchment and associated poorly simulated results, as detailed in Chapter 4.

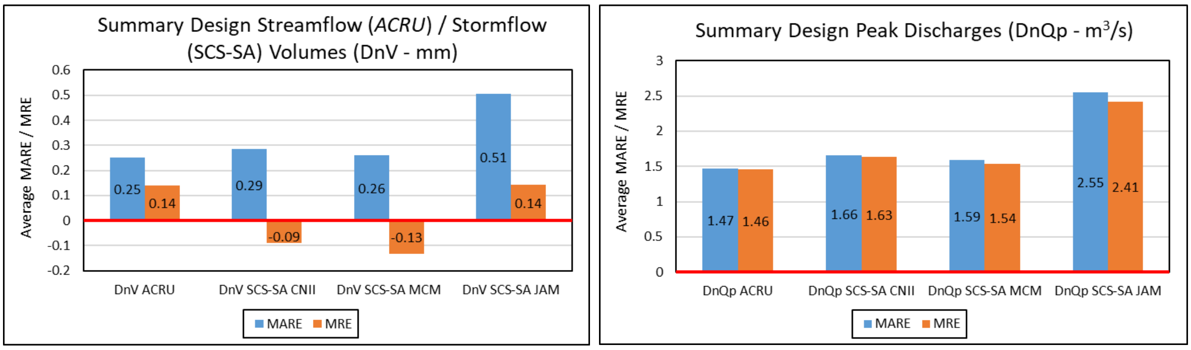

Figure 7.2 Average MARE/MRE values obtained for simulated versus observed Design Streamflow/Stormflow Volumes (DnV) and Design Peak Discharges (DnQp), averaged across all verification catchments, excluding Lambrechtsbos B (G2H010), for both the *ACRU* and SCS-SA models

When comparing the average MARE/MRE values in terms of design streamflow (*ACRU*) and design stormflow (SCS-SA) volumes it is evident that the *ACRU* CSM system produced the lowest MARE (0.25), with a positive MRE (0.14), indicating a tendency to overestimate observed design streamflow volumes in general. The MARE for the SCS-SA model, when applying *CN-II,* is only slightly larger (0.29) compared to the *ACRU* CSM system, however, the MRE is significantly lower (-0.09), indicating a greater tendency to underestimate the observed design streamflow. Both the MARE and MRE when applying the SCS-SA model with the MCM, are only slightly lower, 0.26 and -0.13 respectively, compared to those obtained for the SCS-SA model applying *CN-II*. Therefore, in general the SCS-SA model does not seem to be very sensitive to changes in antecedent soil water for the catchments assessed.

The JAM produced the highest MARE (0.51), with a positive MRE of 0.14. This indicates that, in general, there is an overestimation of the observed design streamflow, however, in many cases there is also significant underestimation, i.e. as indicated by the relatively lower MRE compared to the MARE. Overall, however, the JAM did not perform well and, as alluded to above, this is attributed to: (i) the use of historically assigned rainfall stations with limited record lengths, and (ii) the use of frequency analyses and not extreme value analyses used in the development of the approach and results generated.

In terms of the design peak discharges, the *ACRU* CSM system and the SCS-SA model applying *CN-II* and the MCM provided similar results (Figure 7.2). This again indicates that in terms of design stormflow volumes both the *ACRU* CSM system and the SCS-SA model are producing similar values, and therefore similar design peak discharges are obtained. There are, however, more significant differences between the design streamflow and design stormflow volumes from each model, since the *ACRU* model includes the interflow/baseflow contribution to the total streamflow. Both the *ACRU* CSM system and the SCS-SA model when applying *CN-II* and the MCM generally overestimate design peak discharges, with the *ACRU* CSM system producing the lowest MARE (1.47) and MRE (1.46) and the SCS-SA model applying *CN-II* the highest MARE (1.66) and MRE (1.63) values, i.e. when comparing the results from these three scenarios, excluding those from the SCS-SA JAM. The slightly better results obtained for the *ACRU* CSM system compared to the SCS-SA *CN-II* and MCM may be attributed to explicit accounting of antecedent soil water and an extreme value analysis being performed on the AMS extracted from continuous simulations of daily peak discharges. The general overestimation of the observed design peak discharges is attributed to one or a combination of the following: (i) inaccurate simulations of stormflow volumes for certain design values, (ii) poor approximation of the actual daily rainfall distribution for design events by the synthetic rainfall distribution selected, and (iii) inaccurate estimation of the catchment lag time, i.e. as explained in the analysis of the results from catchment V1H005 and V7H003 above. Once again, the JAM produced the highest MARE (2.55) and MRE (2.41) in terms of design peak discharges.

## 7.6 Conclusions and Recommendations

The objective of this chapter was to compare the performance of the final CSM system proposed in the previous chapter to the performance of the traditional SCS-SA model and associated antecedent soil water adjustment procedures, when the same input information is used.

In summary, the results indicated that the *ACRU* CSM system performed the best in terms of simulating design peak discharges and particularly design streamflow volumes. It was highlighted that the *ACRU* model simulates total streamflow, i.e. stormflow and interflow/baseflow, while the SCS-SA model only simulates stormflow. The contribution of interflow/baseflow to total streamflow for certain catchments was identified to be significant and therefore the results indicate the benefit of using the *ACRU* CSM system over the SCS-SA model. The SCS-SA model results when applying *CN-II* and the MCM were reasonable and highly comparable. The SCS-SA *CN-II* and MCM design streamflow volumes, however, were underestimated in general across all catchments (MRE = -0.09 and -0.13 respectively), compared to the *ACRU* CSM system, i.e. where a general overestimation of design streamflow volumes was observed (MRE = 0.14). In terms of the design peak discharges, with the exception of the SCS-SA JAM, similar estimates were obtained, on average, for all catchments, with the *ACRU* CSM system producing results slightly better than the SCS-SA *CN-II* and MCM, attributed to explicit accounting of antecedent soil water and extreme value analyses being performed on continuous flow sequences. The similarity in the design peak discharge results, however, indicates that the design stormflow volumes simulated by the *ACRU* CSM system and the SCS-SA model when applying *CN-II* and the MCM are similar, which was expected since the *ACRU* CSM system was calibrated against the SCS-SA model *CN-II* values.

The SCS-SA JAM performed particularly poorly in terms of simulating both design stormflow volumes and design peak discharges. It was noted, however, that the results from the JAM are not directly comparable to the results from the *ACRU* simulations and the other two SCS-SA simulations since the method does not use the same rainfall data, and the results are based on a frequency analysis performed on simulated flows and not an extreme value analysis. Conversely, the *CN-II* and MCM SCS-SA simulations and those from the *ACRU* model are based on results obtained from the same rainfall data and from design values obtained from extreme value analyses. The JAM results are particularly poor for the 20-year return period, since only approximately 20 years of rainfall data was available when developing and applying the approach. In addition, for this reason, the method only provides results up to the 20-year return period.

Therefore, from the results presented in this chapter the SCS-SA model applying *CN-II* and the MCM should be used in preference to the JAM, when using the SCS-SA model. However, it is recommended that the *ACRU* CSM system be used to obtain the most accurate results.

# 8. DISCUSSION, CONCLUSIONS AND RECOMMENDATIONS

This chapter contains a discussion and conclusion on Chapters 1 – 7 and includes a summary of how each specific objective was achieved and the novel aspects of the research. Recommendations for future research based on the results obtained from each chapter are also provided.

## 8.1 Research Aim and Objectives

The aim of this study was to further develop and assess the performance of a comprehensive CSM system, to consistently and reliably estimate design flood discharges in small catchments (0 - 100 km$^2$), in South Africa, with a focus on ease of use from a practitioner's point of view.

Specific objectives included: (i) a review of CSM for DFE from a South African perspective, (ii) development of a comprehensive CSM system including the structure of the system and rules on how to apply the system using readily available data, (iii) assessment of the CSM system performance, including any refinements made to the CSM system or additional investigations performed to improve on the CSM system, (iv) assessment of the impact of model configuration and application on the performance of the CSM system and a proposal for a final CSM system for DFE in South Africa, and (v) comparison of the performance of the final CSM system proposed to the traditional SCS-SA approaches.

The main outcomes and results obtained from each of these objectives (Chapters 2 – 7) are summarised and discussed progressively in the sections to follow.

## 8.2 Chapter 2 - Review of Continuous Simulation Modelling for Design Flood Estimation

The review of CSM for DFE highlights the need for updated DFE methods in South Africa and discusses several benefits of the CSM approach over event-based approaches. Some of these include the ability of the method to account for: (i) constant and changing catchment characteristics, (ii) explicit representation of the impact of antecedent soil water conditions on runoff generation, and (iii) a more comprehensive representation of certain critical hydrological processes. A range of models and CSM techniques were reviewed, including both local and international developments and the review includes models where highly satisfactory results were obtained when using a CSM approach to DFE. It was concluded that the CSM approach may be particularly suited to South Africa for the following reasons. In South Africa climate varies significantly across the country, and there is significant regional rainfall variability. Therefore, a CSM approach that accounts for spatial differences in rainfall would be beneficial and appropriate in South Africa. In addition, climate change and land cover change may be accounted for in a conceptually sound manner. The approach has the ability to represent operational catchments, i.e. dams, water transfer schemes, abstractions (e.g. irrigation), and additional water infrastructure systems. The strong seasonality of rainfall in certain parts of the country, certain synoptic conditions and the wide variety of soil types within the country, suggest that in many cases antecedent conditions play a significant role on runoff response, and therefore the ability of the CSM approach to explicitly account for such conditions is a significant benefit. The CSM approach also has significant potential for use in flood forecasting. The forecasting may be used to assist in the management of water related infrastructure. Stochastic rainfall generation and/or rainfall disaggregation techniques may also be included and incorporated into the CSM approach to provide extended and stochastic sequences of rainfall records that may be used to gain greater confidence in design flood estimates, particularly for the higher return period events. Furthermore, the ability of the method to provide coherent simulation of multivariate flood characteristics is identified as a major advantage.

Despite the potential of the approach and the development of national CSM approaches in several countries, including the United Kingdom and Australia, it was identified that the approach is rarely adopted in practice, for the following reasons. The method is too data intensive, and too complicated and time consuming to apply when compared, for example to simple event-based methods. Therefore, following recommendations from the international literature, and preliminary research conducted by Rowe (2015) and Rowe *et al.* (2018), a strong emphasis was placed on the development of a relatively simple CSM approach, with the idea being to base the system on the already widely used SCS-SA event-based approach and readily available land cover and soils classification, i.e. to facilitate adoption of the approach in practice. Rowe (2015) and Rowe *et al.* (2018) investigated a methodology to include land management and hydrological condition classes used in the SCS-SA model into the *ACRU* land cover classification. Further development and investigation of the approach, however, was recommended including the analysis of additional land cover classes, further independent verification at different geographical locations, and verification of the simulated results against observed data, in terms of both streamflow volumes and peak discharges. In addition, further development of a CSM system or methodology for DFE in South Africa was recommended. Confidence in using the SCS-SA classification as a reference, to derive land management practice and hydrological condition classes for use with the *ACRU* model, is gained through the review of contemporary CSM methods applied internationally, e.g. in Italy and Austria, where it was highlighted that the SCS-*CN* methodology is still widely applied as accepted practice, but it is also evident that this sentiment is not unanimous within the literature.

This recommendation to further develop and assess a CSM system for DFE was highlighted as the first step in a list of requirements towards the development of a useable comprehensive CSM system for DFE in South Africa (Table 2.1 – Chapter 2). This is the focus of this research thesis and is addressed through several specific objectives/chapters as summarised and discussed in the sections to follow.

## 8.3 Chapter 3 - Development of a Proposed Comprehensive Continuous Simulation Modelling System for South Africa

Chapter 3 of this thesis describes a comprehensive CSM system for DFE in South Africa. This includes the structure of the CSM system developed which comprises of: (i) the default input information selected and defined for use with the *ACRU* CSM system, such as default values of rainfall, soils and land cover from existing databases, (ii) a comprehensive land cover classification for use with the *ACRU* CSM system, i.e. similar to the SCS-SA land cover classification with updates where necessary to make the *ACRU* land cover classification more compatible with the land cover classes of the default national land cover databases selected, and (iii) a structure of how to apply the model, i.e. level of detail and model options, in order to provide a consistent methodology to implement the approach. This includes using the rules developed by Rowe *et al.* (2018) to represent land cover classes for different land management practices and hydrological conditions within the *ACRU* model. The chapter outlines detailed information about how to model each of the land cover classes listed in the selected default national land cover databases, i.e. the National Land Cover dataset of 2000 (ARC and CSIR, 2005), and an updated 2013/2014 version (DEA and GTI, 2015). For the purpose of defining a comprehensive CSM system this was essential. However, in the assessment and verification of the CSM system developed in subsequent chapters only a limited number of these land cover classes are assessed hydrologically, due mainly to data limitations and the time required to acquire and validate the accuracy of the data. A comprehensive system, however, was proposed and is considered a good baseline for further assessment and verification in the future, with further development and continual improvement to the CSM system required and recommended. The objective of the subsequent chapters was to identify if reasonable results were obtained for selected land cover classes. This was performed to build confidence in the model and the CSM system developed and to justify further development and assessment of the approach for additional land cover classes. It was noted, however, that the limited availability of observed data for specific land cover classes with specific combinations of soils information is limited in South Africa, and therefore verification of the system for certain land cover classes such as agricultural crops and urban areas may be a challenge, particularly when trying to verify the hydrological responses from a single land cover and soil combination, i.e. where most catchments have a range of land cover classes and soil characteristics occurring within the catchment.

## 8.4 Chapters 4 and 5 - Assessment of the Continuous Simulation Modelling System Performance

The specific objective to assess the performance of the CSM system developed for DFE was addressed in Chapters 4 and 5. Chapter 4 provides an example of how to implement the CSM system described in Chapter 3, and assesses and compares the performance of the system to the current default implementation of the *ACRU* model. In the current default implementation of the *ACRU* model, two parameters which strongly influence the daily stormflow response are generally set to default values. This includes: (i) the Quick Flow Response Coefficient (*QFRESP*) which partitions stormflow into a Same Day Response Fraction (*UQFLOW*) and a subsequent delayed stormflow response (defaulted to a value of 0.3 in the *ACRU* model), and (ii) the Critical Response Depth of the Soil (*SMDDEP*), generally default to the depth of the topsoil. In the CSM system, however, rules developed by Rowe *et al.* (2018) are used to parameterise *QFRESP* and *SMDDEP* based on land cover and soils information linked to SCS-

SA *CN*s. Eleven verification catchments distributed across South Africa were used for the assessment.

The initial results indicated that reasonable daily streamflow volumes and design streamflow volumes were simulated when applying both the CSM system developed and the default implementation of the *ACRU* model, within the current *ACRU* structure and computational procedures. Daily peak discharges and design peak discharges, however, were significantly over-simulated. Further investigation of the computation of peak discharge in the current *ACRU* model structure, highlighted an inconsistency between daily simulated stormflow volumes and the volume of stormflow used in the daily stormflow peak discharge equation. Therefore, a revision was applied to the fraction of simulated daily stormflow used in the peak discharge equation within the *ACRU* model. This corrected the inconsistency and significantly improved the results. Overall, considering both daily and design streamflow volumes and peak discharges, the CSM system was identified to provide the most accurate results, motivating for further development and assessment of the CSM system. The results indicated a tendency of the default implementation of the *ACRU* model to underestimate daily streamflow volumes and design streamflow volumes. In addition, the ability of the CSM system to account for differences in hydrological responses for different soils, land management practices and hydrological conditions, which are used to parameterise the *QFRESP* and *SMDDEP* parameters in *ACRU* (which are currently set to default values), is identified as a major advantage over the default implementation of the *ACRU* model. Consequently, the CSM system was selected as the most suitable method and used in all subsequent assessments.

Despite improvements in the simulated peak discharges when applying the revision to the peak discharge computation, over-simulation of the daily and design peak discharges in general was still evident. This was attributed to one or a combination of the following: (i) the surface runoff contribution to peak discharge being too high, (ii) incorrect estimation of catchment lag time, and (iii) the inability of the single UH approach (Equation 4.3) to account for the actual distribution of daily rainfall, i.e. the rainfall intensity, on a given day.

Based on the results and recommendations from Chapter 4, Chapter 5 investigated the simulation of the stormflow contribution to peak discharge in detail for two case study catchments with high quality observed streamflow and sub-daily rainfall data. The performances of both the single UH approach and the incremental UH approach were assessed, including the sensitivity of each approach to estimated parameters versus parameters determined from the observed data. The results once again indicated the sensitivity of the peak discharge computation to the stormflow volume used. The incremental UH approach consistently provided superior results compared to the single UH approach, both when using parameters obtained from observed data, and when using estimated and synthetic information. The incremental UH approach was identified to be more sensitive to the use of synthetic daily rainfall distributions compared to estimated lag times, i.e. when observed data were replaced with these estimates.

The following conclusions were drawn, based on the results obtained from Chapters 4 and 5. Regardless of how the *QFRESP* and *SMDDEP* parameter values are estimated in the *ACRU* model, the revision applied to the *ACRU* peak discharge computation in this research should be applied in all future applications of the *ACRU* model in order to provide more realistic peak discharge estimates. In this research, the *QFRESP* and *SMDDEP* parameter values are parameterised based on SCS-SA *CN*s for specific land cover and soils combinations. The simulation of daily streamflow from a catchment in the *ACRU* model is very sensitive to these parameters and therefore obtaining a best estimate of them is essential and should be considered carefully. Since the parameters have been derived from SCS-SA *CN*s, which vary with soils and land cover classes, particular care in obtaining accurate soils and land cover information is highly recommended when applying the CSM system developed. In terms of simulating the stormflow contribution to peak discharge, the Schmidt and Schulze (1984) estimated lag times and synthetic rainfall distributions (however to a lesser extent) were identified to be reasonable estimates of these parameters. The preliminary results from the two case study catchments indicate that the incremental UH approach provides more accurate peak discharge estimates compared to the single UH approach. Recommendations, however, were made to further verify this observation using all eleven verification catchments used in the assessment of the CSM system developed, with the results summarised and discussed in the next section.

## 8.5 Chapter 6 - Impact of Model Configuration on the Performance of the Continuous Simulation Modelling System and a Proposal for a Final System

Chapter 6 contains the assessment of the impact of model configuration and parameter estimation on the performance of the CSM system developed and assessed in the previous chapters. The chapter addresses two specific objectives, as summarised and discussed below.

The first objective was to identify if the incremental UH approach with the Schmidt and Schulze (1984) estimated lag and synthetic daily rainfall distributions (Weddepohl, 1988) consistently performs better than the single UH approach, also using the Schmidt and Schulze (1984) estimated lag time, for all verification catchments used in the assessment of the CSM system in Chapter 4. Based on the results it was concluded that the incremental UH approach performs better than the single UH approach and therefore the incremental UH approach is established as the default peak discharge computation procedure in the CSM system.

The second objective of this Chapter was to use the results obtained from Objective 1, referred to as the "Current CSM System" scenario (i.e. applying the incremental UH approach, site-specific land cover and soils information and the Schmidt and Schulze (1984) estimated lag time), and compare them to those obtained for several additional scenarios where different sources of input information are used. This included default national land cover and soils maps as well as different options to estimate catchment lag time.

From the results obtained it was concluded that the "Current CSM system", i.e. with site-specific land cover and soils information and the Schmidt and Schulze (1984) estimated lag time produced the best results. The results where SCS-SA soil groups were estimated from national SCS soil group maps, were significantly worse compared to those obtained for the "Current CSM System" scenario. The results obtained when deriving soils information from the Schulze and Schütte 2018 SCS Soils map were substantially better than when the Schulze (2012) soils map was used. Therefore, the Schulze and Schütte 2018 SCS Soils map was established as the default SCS-SA soils information to use with the CSM system, when site-specific information is not available. When using the NLC 2000 maps to obtain land cover information the results were also relatively poor compared to those obtained for the "Current CSM System". A degree of conservatism, however, to rather overestimate daily and design values, was incorporated into the default land cover maps used for this scenario, which explains the deterioration in the results. In the absence of site-specific information the national land cover maps provide reasonable information and have been established as the default land cover information to use with the CSM system. *ACRU* specific soils information should be obtained from the default values assigned to SCS-SA soil groups (Table 3.4) by Rowe (2015), and not from the national soils map developed by Schulze and Horan (2008). The CSM system was calibrated using the default information and therefore explains why the results are better when using these inputs with the CSM system. The Schmidt and Schulze (1984) lag equation is recommended as the default lag equation to use with the CSM system. In summary, site-specific information related to land cover and soils should be used in preference to the default national land cover and soils maps, where available. In addition, when using the national land cover and soils maps the information should be verified as best as possible.

In conclusion, although the results when using the default soils and land cover inputs were not particularly good, the CSM system provides a consistent and conceptually sound approach to estimate changes in streamflow response for different land cover and soils conditions. It is acknowledged that the CSM system has relied heavily on the SCS-SA land cover classification. Consequently, it is possible that the two models may provide similar results. Therefore, an assessment of how the results from the CSM system developed compare to those obtained from the event-based SCS-SA model was necessary. This was addressed in Chapter 7, with a summary and discussion of the results presented in the next section.

## 8.6 Chapter 7 - Comparison of the Performance of the Final *ACRU* Continuous Simulation Modelling System Proposed to the Traditional SCS-SA Approaches

Chapter 7 contains the comparison of the performance of the final *ACRU* CSM system proposed to the performance of the traditional SCS-SA approaches when using the same input information in both approaches. This was considered as an essential final step to justify further implementation and/or development of the CSM system in the future. In addition, the assessment provided the opportunity to assess the performance of the traditional SCS-SA model when applying the initial catchment Curve Number (*CN-II*), the Median Condition Method (MCM) and the Joint Association Method (JAM).

In summary the results indicate that the *ACRU* CSM system performed the best in terms of simulating design peak discharges and particularly design streamflow volumes. It was highlighted that the *ACRU* model simulates total streamflow, i.e. stormflow and interflow/baseflow, while the SCS-SA model only simulates stormflow. The contribution of interflow/baseflow to total streamflow for certain catchments was identified to be significant and therefore the results indicate the benefit of using the *ACRU* CSM system over the SCS-SA model. The SCS-SA model when applying *CN-II* and the MCM provided reasonable results, however, underestimated design streamflow volumes in general across all catchments (MRE = -0.09 and -0.13 respectively), compared to the *ACRU* CSM system where a general overestimation of design streamflow volumes was observed (MRE = 0.14).

The SCS-SA JAM performed particularly poorly. This is attributed to the specific data and procedures used in the development of the approach, which meant that the results were not directly comparable to the other model results. The JAM uses rainfall data from rainfall stations assigned to each homogenous response zone, i.e. with record lengths restricted to the period when the method was developed, and the results are based on a frequency analysis performed on simulated flows. Conversely, the driver rainfall station assigned to each catchment in the assessment of the CSM system, was used with the other two SCS-SA methods (*CN-II* and MCM), and the results were based on extreme value analyses. The JAM results were particularly poor for the 20-year return period. This is as a result of only approximately 20 years of rainfall data being available during the development of the approach and a frequency analysis being performed on the simulated flows and not an extreme value analysis. This also explains why the JAM only provides estimates up to the 20-year return period.

In terms of the design peak discharges, with the exception of the SCS-SA JAM, similar estimates were obtained on average for all catchments. The similarity in the results obtained for the SCS-SA model when applying *CN-II* and the MCM, in terms of both design stormflow volumes and design peak discharges, indicates that the model is not very sensitive to the adjustments for antecedent soil water for the catchments investigated. Based on the results obtained it is recommended that the *ACRU* CSM system be used in preference to the SCS-SA model when estimating design floods for small catchments in South Africa. In addition, if the SCS-SA model is being applied the *CN-II* method and the MCM should be used in preference to the JAM. Another consideration for future research is to use the results generated by the

CSM system defined in this research to update the SCS-SA MCM and JAM, as detailed in a subsequent section below summarising all the recommendations identified from this research.

## 8.7 Achievement of Research Aim and Novel Aspects of the Research

The aim of this research was to further develop and assess the performance of a comprehensive CSM system, to consistently and reliably estimate design flood discharges in small catchments (0 - 100 km$^2$) in South Africa, with a focus on ease of use from a practitioner's point of view.

This aim has been achieved through several specific objectives, and a comprehensive CSM system for DFE in South Africa has been developed and proposed, that is relatively simple and easy to use, with a structure and land cover classification similar to that of the SCS-SA model. The CSM system developed has been assessed and verified against observed data and through the verifications and assessments an inconsistency in the *ACRU* peak discharge computation was identified. The inconsistency was resolved in a novel and conceptually sound manner and provides improved estimates of peak discharges in the *ACRU* model. In addition, the assessments and investigations performed highlighted several components of the CSM system that require further development to improve on and further verify the CSM system developed. The performance of the *ACRU* CSM system developed has also been compared to that of the widely applied traditional SCS-SA model and associated approaches and the advantages of the CSM system over the SCS-SA event-based approaches highlighted.

The novel aspects of the research can be summarised as follows:

(i) Development and assessment of a comprehensive CSM system for DFE in South Africa, applicable to small catchments (0 – 100 km$^2$);

(ii) Explicit representation and inclusion of land management practices and hydrological condition classes for natural, agricultural and urban land cover classes into a final land cover classification proposed for the CSM system and the *ACRU* model;

(iii) Linked to Point (ii), relationships between SCS-SA *CN*s and the *ACRU QFRESP* and *SMDDEP* parameters, which are currently generally set to default values, have been developed to represent the aforementioned land management and hydrological condition classes;

(iv) Identification and establishment of default national land cover and soils maps to apply with the CSM system, i.e. for use especially in the absence of site-specific information, and associated default land cover classes assigned to the national land cover datasets;

(v) Recommendations regarding the default datasets of actual land cover information and associated classifications and parameters required to model these actual land cover classes in the *ACRU* CSM system, and in addition, owing to the links between the land cover classification developed for the *ACRU* CSM system and that of the traditional SCS-SA model, this information is also applicable to the SCS-SA model;

(vi) An improvement made to the peak discharge computation in the *ACRU* model with the use of a new approach to partition stormflow generated on a particular day into runoff leaving the catchment on the same day and delayed interflow;

(vii) New knowledge on the performance and sensitivity of the single and incremental UH approaches, applied in the *ACRU* model to estimate the stormflow contribution to peak discharge;

(viii) New knowledge on the performance of the traditional SCS-SA model and its associated approaches compared to that of a comprehensive CSM system developed for South Africa;

(ix) New knowledge on the performance of a comprehensive CSM system for DFE in terms of accurately simulating both daily streamflow volumes and peak discharges as well as design streamflow volumes and peak discharges; and the

(x) Identification of additional research needs related to improved estimation of the sub-daily distribution of daily rainfall within the *ACRU* model, links between the distribution of daily rainfall and catchment lag time, together with the need to further verify and possibly recalibrate *CN*s for South Africa.

In summary, it is envisaged that the CSM system developed and proposed in this research is a crucial first step towards further development and adoption of a comprehensive useable CSM approach to DFE for small catchments in South Africa. Over time, additional aspects such as stochastically generated rainfall and daily rainfall disaggregation methods may be refined and included in the system. In addition, climate change and land cover change scenarios may be simulated with the CSM system in the future, based on results from the latest climate models and projected trends in rainfall, as well as projected land cover changes. This may include a

GCM ensemble or Monte Carlo type approach. Such investigations, however, are dependent on a reliable system that has been validated and verified, such as the system developed and described in this research.

## 8.8 Recommendations for Future Research

Based on the research gaps identified, investigations performed and results obtained in this research, through the various chapters, the recommendations for future research are summarised as follows:

(i) To further develop the CSM system defined and assessed in this research, and to establish a comprehensive useable product for practitioners to apply, the following recommendations identified from the literature review (Table 2.1 – Chapter 2) still need to be addressed: further development, assessment and inclusion of national stochastic rainfall generation and/or disaggregation techniques; compilation of the CSM system and additional developments into a user-friendly, simple, software tool that is attractive to consultants and government organisations (e.g. DWS, SANRAL), and provision of training courses, workshops and user manuals related to the software; as well as continual updating, refinement and improvement of the approach including, for example, flood routing routines and flood forecasting. In addition, refinements and improvements to the final *ACRU* land cover classification should be considered in future research, particularly with regards to possibly explicitly representing the three forestry genomes typically cultivated in South Africa.

(ii) Difficulties associated with obtaining observed data for research catchments and the poor quality of climate and hydrological data in South Africa are highlighted in this research. Therefore there is an urgent need to collate, error check and standardise climate and hydrological data from various sources into a single and easily obtainable national database. If this is not performed timeously, this valuable data from research catchments that is irreplaceable will be lost.

(iii) Based on the results obtained in this research regarding the simulation of peak discharges it was identified that the Schmidt and Schulze (1984) estimated catchment lag time and synthetic rainfall distributions developed by Weddepohl (1988) are reasonable average estimates of these parameters required to estimate daily peak discharges. It was noted, however, that these parameters vary signficantly from day-to-day and the peak discharge computation is sensitive to both these inputs. Consequently, it is strongly recommended that methods to better estimate the distribution of daily rainfall and catchment lag time on a day-to-day basis be investigated and/or developed. It is also recommended that priority be given to the development of a methodology to more adequately estimate the distribution of daily rainfall, due to the sensitivity of the incremental UH approach to this input and relationships identified between rainfall intensity and catchment lag time, i.e. suggesting that lag time may be adjusted based on rainfall intensity.

(iv) Based on the sensitivity of the CSM system to land cover and soils information, it is recommended that verification and/or recalibration of the *CN*s and associated *ACRU QFRESP* and *SMDDEP* parameter values for the land cover and soils combinations, listed in the updated SCS-SA and final *ACRU* land cover classifications, be considered in future research and in further development of the approach. Furthermore, an assessment of the impact of catchment area and slope on the parameterisation of the QFRESP parameter in particular should also be considered in future research. In addition, consideration of including the detailed land use management scenarios provided in the MUSLE Handbook should be considered in future research. Another possible consideration for future research is to re-look the SCS equations from 1st principles and develop improved equations. This, however, would likely be a significant undertaking and sufficient observed data would need to be sourced, if available, to validate and verify the approach.

(v) Linked to the previous point on the sensitivity of the CSM system to land cover and soils information, it is recommended that further refinement and improvement of default estimates of land cover and soils information be considered in future research, including further refinement of the SCS-SA soil group map developed by Schulze and Schütte (2018).

(vi) As already highlighted above, the Schmidt and Schulze (1984) estimated catchment lag time was identified to be a reasonable estimate, and superior to the SCS lag equation. The $\bar{I}30$ parameter used in the Schmidt and Schulze (1984) lag equation in this research was obtained using the 2-year return period maximum 1-day rainfall calculated from the daily rainfall files used as input to the *ACRU* model, and applying a multiplication factor defined for each specific region. In future research a comparison and assessment of the impact that different Ī30 estimates have on the Schmidt and Schulze (1984) estimated lag time and the consequent impacts on the simulated peak discharges is recommended, this may include Ī30 estimates derived from the gridded RLMA&SI values (Smithers and Schulze, 2000).

(vii) In terms of the SCS-SA MCM and JAM the *CN* adjustment is based on the limited rainfall data, spatial coverage, land cover and soils combinations, and *ACRU* modelling capabilities available during the 1980's when these methods were developed (Schmidt and Schulze, 1987a). This point is particularly relevant to the SCS-SA JAM where a frequency analysis was conducted on simulated flows and consequently the method is completely dependent on the rainfall data available and used at the time. Consequently, the method was not recommended for estimating design stormflow beyond the 20-year return period. Therefore, an additional recommendation is to use the results from, and methodology applied in, this research to comprehensively update the SCS-SA MCM and JAM. In terms of the JAM this involves running the *ACRU* model with updated rainfall and climate data, i.e. with the extended records currently available, and land cover and soils combinations, and performing frequency analyses or alternatively extreme value analyses on the simulated flows. This will provide updated design stormflow and peak discharge values for defined homogeneous response zones, i.e. either the quaternary or quinary catchments. While performing these simulations, additional information such as simulated daily soil water deficits, i.e. provided as an optional output in the *ACRU* model, may be used to update the MCM method. This will involve performing a frequency analysis on the simulated daily soil water deficits, and using the 50th percentile soil water deficit to adjust the original average catchment *CN* (*CN-II*). Additional experimentation may also be performed, e.g. using different soil water deficit percentiles for different return periods.

The recommendations for future research, in conjunction with the CSM system developed and proposed in this research, may be used to further develop a comprehensive useable CSM system for DFE in South Africa. A baseline comprehensive approach, however, has been defined, verified and proposed which may be applied for DFE in small catchments in South Africa.

# 9. REFERENCES

Acocks, J. 1988. *Veld types of South Africa*. Botanical Survey of South Africa, Memoirs, 57. Botanical Research Institute, Pretoria, South Africa.

Ahn, J, Cho, W, Kim, T, Shin, H and Heo, J. 2014. Flood Frequency Analysis for the Annual Peak Flows Simulated by an Event-Based Rainfall-Runoff Model in an Urban Drainage Basin. *Water* 6: 3841-3863.

Alexander, W. 2002. Statistical analysis of extreme floods. *Journal of the South African Institution of Civil Engineering* 44 (1): 20-25.

ARC and CSIR. 2005. *National Land Cover (2000)*. Produced by a consortium of the Council for Scientific and the Industrial Research (CSIR) and the Agricultural Research Council (ARC), Pretoria, South Africa.

Arnaud, P, Cantet, P and Odry, J. 2017. Uncertainties of flood frequency estimation approaches based on continuous simulation using data resampling. *Journal of Hydrology* 554 360-369.

Ball, J.2013. Estimation of Design Floods using Continuous Simulation. *Floodplain Management Australia (FMA) National Conference*, pp. 1-16. Floodplain Management Australia, Newcastle, NSW, Australia.

Ball, J, Babister, M, Nathan, R, Weeks, B, Weinmann, E, Retallick, M and Testoni, I. 2016. *Australian Rainfall and Runoff: A Guide to Flood Estimation*. Australian Rainfall and Runoff (ARR), Commonwealth of Australia.

Bennett, J, Robertson, D, Lal, D, Wang, Q, Enever, D, Hapuarachchi, P and Tuteja, N. 2014. A System for Continuous Hydrological Ensemble Forecasting (SCHEF) to lead times of 9 days. *Journal of Hydrology* 519: 2832-2846.

Bergström, S. 1976. *Development and application of a conceptual model for Scandinavian catchments*. SMHI Report RH07. Swedish Meteorological and Hydrological Institute (SMHI), Report RH07, Norrkoping, Sweden.

Bergström, S. 1992. *The HBV Model - Its Structure and Applications*. SMHI Report RH No. 4. Swedish Meteorological and Hydrological Institute (SMHI) Report RH No. 4, Norrkoping, Sweden.

Beven, K. 1987. Towards the use of catchment geomorphology in flood frequency predictions. *Earth Surface Processes and Landforms* 12: 69-82.

Blazkova, S and Beven, K. 2004. Flood frequency estimation by continuous simulation of subcatchment rainfalls and discharges with the aim of improving dam safety assessment in a large basin in the Czech Republic. *Journal of Hydrology* 292: 153–172.

Blazkova, S and Beven, K. 2009. A limits of acceptability approach to model evaluation and uncertainty estimation in flood frequency estimation by continuous simulation: Skalka catchment, Czech Republic. *Water Resources Research* 45 (W00B16): 1-12.

Blöschl, G, Sivapalan, M, Wagener, T, Viglione, A and Savenije, H. 2013. *Runoff Predictions in Ungauged Basins: Synthesis across Processes, Places and Scales*. Cambridge University Press, University Printing House, Cambridge CB2 8BS, United Kingdom.

Boughton, W and Droop, O. 2003. Continuous simulation for design flood estimation—a review. *Environmental Modelling & Software* 18: 309–318.

Boughton, W, Muncaster, S, Srikanthan, R, Weinmann, P and Mein, R.1999. Continuous simulation for design flood estimation - a workable approach. *In: Proceedings of the WATER99 Joint Congress*, pp. 178–183. Institution of Engineers, Australia, Canberra, Brisbane, ACT, Australia.

Boughton, W, Srikanthan, R and Weinmann, E. 2000. Benchmarking a new design flood estimation system. *In: Proceedings of the Hydro 2000 Hydrology and Water Resources Symposium*, pp. 570–575. Institution of Engineers, Australia, Canberra, Brisbane, ACT, Australia.

Brocca, L, Melone, F and Moramarco, T. 2011. Distributed rainfall-runoff modelling for flood frequency estimation and flood forecasting. *Hydrological Processes* 25 (18): 2801-2813.

Calver, A. 1996. Development and experience of the 'TATE' rainfall-runoff model. *Proc. of the Institution of Civil Engineers: Water, Maritime and Energy* 118: 168-176.

Calver, A, Crooks, S, Jones, D, Kay, A, Kjeldsen, T and Reynard, N. 2004. *Flood Frequency Quantification for Ungauged Sites using Continuous Simulation: a UK approach*. Centre for Ecology & Hydrology, Wallingford, United Kingdom.

Calver, A, Crooks, S, Jones, D, Kay, A, Kjeldsen, T and Reynard, N. 2005. *National river catchment flood frequency method using continuous simulation*. R&D Technical Report FD2106/TR. Research Report to Defra, Centre for Ecology & Hydrology, Wallingford, United Kingdom.

Calver, A and Lamb, R. 1995. Flood frequency estimation using continuous rainfall-runoff modelling. *Physics and Chemistry of the Earth* 20 (5-6): 479-483.

Calver, A, Lamb, R, Kay, A and Crewett, J. 2001. *The continuous simulation method for river flood frequency estimation*. Defra Project FD0404 Final Report, Centre for Ecology & Hydrology (CEH), Wallingford, United Kingdom.

Calver, A, Lamb, R and Morris, S. 1999. *Flood frequency estimation using continuous runoff modelling*. Proc. Institution of Civil Engineers, Water, Maritime & Energy.

Calver, A, Stewart, E and Goodsell, G. 2009. Comparative analysis of statistical and catchment modelling approaches to river flood frequency estimation. *Journal of Flood Risk Management* 2: 24–31.

Cameron, D. 2006. An application of the UKCIP02 climate change scenarios to flood estimation by continuous simulation for a gauged catchment in the northeast of Scotland, UK (with uncertainty). *Journal of Hydrology* 328 212–226.

Cameron, D, Beven, K, Tawn, J, Blazkova, S and Naden, P. 1999. Flood frequency estimation by continuous simulation for a gauged upland catchment (with uncertainty). *Journal of Hydrology* 219 169–187.

Cameron, D, Beven, K, Tawn, J and Naden, P. 2000. Flood frequency estimation by continuous simulation (with likelihood based uncertainty estimation). *Hydrology and Earth System Sciences* 4 (1): 23-34.

Camici, S, Tarpanelli, A, Brocca, L, Melone, F and Moramarco, T. 2011. Design soil moisture estimation by comparing continuous and storm-based rainfall-runoff modeling. *Water Resources Research* 47 (W05527): 1-18.

CDNGI. 2013. Chief Directorate National Geo-spatial Information. [Internet]. National Department of Rural Development and Land Reform. Available from: www.ngi.gov.za. [Accessed: 2013].

Chetty, K and Smithers, J. 2005. Continuous simulation modelling for design flood estimation in South Africa: Preliminary investigations in the Thukela catchment. *Physics and Chemistry of the Earth, Parts A/B/C* 30 (11–16): 634-638.

Chiew, F, Peel, M and Western, A. 2002. Application and testing of the simple rainfallrunoff model SIMHYD. In V.P. Singh & D.K. Frevert (Eds.). *Math. Models of Small Watershed Hydrol. & Applications. Colorado: Water Resour. Pub.* 335–367.

Clothier, A and Pegram, G. 2002. *Space-Time Modelling of Rainfall Using the String of Beads Model: Integration of Radar and Raingauge Data*. WRC Report No. 1010/1/02. Water Research Commission, Pretoria, South Africa.

COST. 2013. *A Review of Applied Methods in Europe for Flood-Frequency Analysis in a Changing Environment. WG4: Flood Frequency Estimation Methods and Environmental Change*. COST Action ES0901. European Cooperation in Science and Technology, Centre for Ecology & Hydrology, Wallingford, United Kingdom.

Crawford, N and Burges, S. 2004. History of the Stanford Watershed Model. *Water Resources Impact* 6 (2): 1-3.

Cu, T. 2016. Enhancement of Design Flood Estimation using Continuous Simulation. Unpublished thesis, School of Civil and Environmental Engineering, Faculty of Engineering and Information Technology, University of Technology, Sydney, Australia.

DEA and GTI. 2015. *South African National Land Cover Dataset (2013/2014)*. Produced by GeoTerraImage Pty Ltd (GTI) for the Department of Environmental Affairs (DEA), Pretoria, South Africa.

Denys, F, Görgens, A and Beuster, H. 2006. *EX-HYD User Manual*. WRC Report No. K5/1420. Water Research Commission, Pretoria, South Africa.

Devi, G, Ganasri, B and Dwarakish, G. 2015. A Review on Hydrological Models. *Aquatic Procedia* 4: 1001–1007.

DHI. 2017. Mike Urban - Integrated Urban Water Modelling. [Internet]. Mike Powered by DHI. Available from: http://www.mikepoweredbydhi.com/products/mike-urban. [Accessed: 26 April 2017].

Droop, O. 2001. *Literature Review of Distributed Modelling*. Research Report No. 1/01 Gilbert and Associates, Brisbane, Australia.

Droop, O and Boughton, W. 2002. *Integration of WBNM into a continuous simulation system for design flood estimation*. Research Report No. 2/02, Gilbert & Associates, Brisbane, Australia.

Du Plessis, J and Burger, G. 2015. Investigation into increasing short-duration rainfall intensities in South Africa. *Water SA* 41 (3): 416-424.

ESRI. 2016. *ArcGIS Desktop: Release 10.4*. Environmental Systems Research Institute, Redlands, California, United States.

FloodList. 2016. FloodList – Reporting floods and flooding news since 2008. [Internet]. Available from: http://www.floodlist.com. [Accessed: 20 September 2016].

Frezghi, M. 2005. The development and assesment of a methodology to improve the estimation of the spatial distribution of rainfall. Unpublished thesis, School of Bioresources Engineering and Environmental Hydrology, University of KwaZulu-Natal, Pietermartizburg, South Africa.

GEOTERRAIMAGE. 2015. *2013 - 2014 South African National Land-Cover Dataset: Data User Report and MetaData*. Geoterra Image (Pty) Ltd, Pretoria, South Africa.

Gericke, O. 2018. Personal communication, Department of Civil Engineering, Central University of Technology, Free State, Bloemfontein, South Africa, 22 August 2018.

Gericke, O and Smithers, J. 2014. Review of methods used to estimate catchment response time for the purpose of peak discharge estimation. *Hydrological Sciences Journal* 59 (11): 1935-1971.

Gericke, O and Smithers, J. 2016. Derivation and verification of empirical catchment response time equations for medium to large catchments in South Africa. *Hydrological Processes* 30: 4384–4404.

Gericke, O and Smithers, J. 2017. Direct estimation of catchment response time parameters in medium to large catchments using observed streamflow data. *Hydrological Processes* 31 (5): 1125-1143.

Gericke, O and Smithers, J. 2018. An improved and consistent approach to estimate catchment response time parameters: Case study in the C5 drainage region, South Africa. *Journal of Flood Risk Management* 11 (S1): S284-S301.

Görgens, A. 2007. *Joint Peak-Volume (JPV) Design Flood Hydrographs for South Africa*. WRC Report No 1420/3/07. Water Research Commission, Pretoria, South Africa.

Görgens, A, Lyons, S, Hayes, L, Makhabane, M and Maluleke, D. 2007. *Modernised South African Design Flood Practice in the Context of Dam Safety*. WRC Report No. 1420/2/07. Water Research Commission, Pretoria, South Africa.

Grimaldi, S, Petroselli, A and Serinaldi, F. 2012. A continuous simulation model for design-hydrograph estimation in small and ungauged watersheds. *Hydrological Sciences Journal* 57 (6): 1035-1051.

Gush, M, Scott, D, Jewitt, G, Schulze, R, Lumsden, T, Hallowes, L and Görgens, A. 2002. *Estimation of Streamflow Reductions Resulting from Commercial Afforestation in South Africa*. Report No. TT 173/02. Water Research Commission, Stellenbosch, South Africa.

Haberlandt, U and Radtke, I. 2013. Derived flood frequency analysis using different model calibration strategies based on various types of rainfall–runoff data – a comparison. *Hydrology and Earth System Sciences* 10 (8): 10379–10417.

Haberlandt, U and Radtke, I. 2014. Hydrological model calibration for derived flood frequency analysis using stochastic rainfall and probability distributions of peak flows. *Hydrol. Earth Syst. Sci.* 18 (1): 353-365.

Hargreaves, G and Samani, Z. 1985. Reference crop evapotranspiration from temperature. *Transactions of the American Society of Agricultural Engineers* 1 96-99.

Hawkins, R. 1978. Runoff curve numbers with varying site moisture. *Journal of Irrigation and Drainage Division, American Society of Civil Engineers* 104: 389-398.

Hosking, J and Wallis, J. 1997. Regional Frequency Analysis: An Approach Based on L-Moments. *Cambridge University Press, Cambridge, United Kingdom*

Hrachowitz, M, Savenije, H, Blöschl, G, McDonnell, J, Sivapalan, M, Pomeroy, J, Arheimer, B, Blume, T, Clark, M, Ehret, U, Fenicia, F, Freer, J, Gelfan, A, Gupta, H, Hughes, D, Hut, R, Montanari, A, Pande, S, Tetzlaff, D, Troch, P, Uhlenbrook, S, Wagener, T, Winsemius, H, Woods, R, Zehe, E and Cudennec, C. 2013. A decade of Predictions in Ungauged Basins (PUB)—a review. *Hydrological Sciences Journal* 58 (6): 1198-1255.

IOH. 1999. *Flood Estimation Handbook. 5 volumes*. Institute of Hydrology, Wallingford, United Kingdom.

Kang, M, Goo, J, Song, I, Chun, J, Her, Y, Hwang, S and Park, S. 2013. Estimating design floods based on the critical storm duration for small watersheds. *Journal of Hydro-environment Research* 7: 209-218.

Kienzle, S and Schulze, R.1995. Simulating daily streamflows in the Mgeni Catchment under past, present and future land uses. *in: Proceedings of the 7th South African Hydrology Symposium*, Grahamstown, South Africa.

Kjeldsen, T. 2007. *The Revitalised FSR/FEH Rainfall-Runoff Method*. Flood Estimation Handbook, Supplementary Report No. 1. Centre for Ecology & Hydrology, Wallingford, United Kingdom.

Kjeldsen, T. 2015. How reliable are design flood estimates in the UK? *Journal of Flood Risk Management* 8 (3): 237-246.

Knoesen, D. 2005. The development and assessment of techniques for daily rainfall disaggregation in South Africa. Unpublished thesis, School of Bioresources Engineering and Environmental Hydrology, University of KwaZulu-Natal, Pietermartizburg, South Africa.

Knoesen, D and Smithers, J. 2009. The development and assessment of a daily rainfall disaggregation model for South Africa. *Hydrological Sciences Journal* 54 (2): 217-233.

Kruger, A. 2006. Observed Trends in Daily Precipitation Indices in South Africa: 1910–2004. *International Journal of Climatology* 26: 2275–2285.

Kruger, A and Nxumalo, M. 2017. Historical rainfall trends in South Africa: 1921–2015. *Water SA* 43 (2): 285-297.

Kusangaya, S, Warburton, M, Archer van Garderen, E and Jewitt, G. 2014. Impacts of climate change on water resources in southern Africa: A review. *Physics and Chemistry of the Earth, Parts A/B/C* 67–69: 47-54.

Lamb, R. 1999. Calibration of a conceptual rainfall-runoff model for flood frequency estimation by continuous simulation. *Water Resources Research* 35 (10): 3103-3114.

Lamb, R, Faulkner, D, Wass, P and Cameron, D. 2016. Have applications of continuous rainfall–runoff simulation realized the vision for process-based flood frequency analysis? *Hydrological Processes* 30: 2463–2481.

Lawrence, D, Paquet, E, Gailhard, J and Fleig, A. 2014. Stochastic semi-continuous simulation for extreme flood estimation in catchments with combined rainfall–snowmelt flood regimes. *Natural Hazards and Earth System Sciences* 14: 1283–1298.

Ling, F, Pokhrel, P, Cohen, W, Peterson, J, Blundy, S and Robinson, K. 2015. *Revision Project 8: Use of Continuous Simulation Models for Design Flood Estimation, Revision Project 12: Selection of an Approach. Stage 3 Report, ARR Report Number P12/S3/008*. Engineers Australia, Barton, Australia.

Lorentz, S and van Zyl, A. 2003. *Predicting the Impact of Farming Systems on Sediment Yield in the Context of Integrated Catchment Management*. WRC Report No: 1059/1/03. Water Research Commission, Pretoria, South Africa.

Lynch, S. 2003. *Development of a Raster Database of Annual, Monthly and Daily Rainfall for Southern Africa*. WRC Report No. 1156/1/03. School of Bioresources Engineering and Environmental Hydrology, University of Natal, Pietermaritzburg, South Africa.

Martinez, G and Gupta, H. 2010. Toward improved identification of hydrological models : A diagnostic evaluation of the " abcd " monthly water balance model for the conterminous United States. *Water Resources Research* 46: 1–21.

Mathevet, T. 2005. *Which Global Rainfall–Runoff Models in an Hourly time-step? Development and Empirical Comparison of Models on a Large Sample of Watersheds*. PhD Thesis. AgroParisTech (Ex. ENGREF), Paris, France.

Mishra, S and Singh, V. 2003. *Soil Conservation Service Curve Number (SCS-CN) Methodology*. Kluwer Academic Publishers, Dordrecht, Netherlands.

Moore, R. 1985. The probability-distributed principle and runoff production at point and basin scales. *Hydrological Sciences Journal* 30 (2): 273-297.

Mouelhi, S, Madani, K and Lebdi, F. 2013. A Structural Overview through GR(s) Models Characteristics for Better Yearly Runoff Simulation. *Open Journal of Modern Hydrology* 3: 179-187.

Nathan, R and Ball, J. 2016. *Approaches to Flood Estimation, Book 1, Chapter 3 in Australian Rainfall and Runoff: A Guide to Flood Estimation*. Australian Rainfall and Runoff (ARR), Commonwealth of Australia.

Nathan, R and Ling, F. 2016. *Types of Simulation Approaches, Book 4, Chapter 3 in Australian Rainfall and Runoff: A Guide to Flood Estimation*. Australian Rainfall and Runoff (ARR), Commonwealth of Australia.

Nathan, R and McMahon, T. 1990. Evaluation of automated techniques for baseflow and recession analyses. *Water Resources Research* 26 (7): 1465–1473.

Nathan, R and Weinmann, E. 2013. *Discussion Paper: Monte Carlo Simulation Techniques. Final Report AR&R D2*. Engineers Australia, Barton, Australia.

NERC. 1975. *Flood Studies Report*. Natural Environment Research Council, London, United Kingdom.

Newton, D and Walton, R.2000. Continuous Simulation for Design Flood Estimation in the Moore River Catchment, Western Australia. *In Hydro 2000 Hydrology and Water Resources Symposium*, pp. 475–480. Perth, Australia.

Odry, J and Arnaud, P. 2017. Comparison of Flood Frequency Analysis Methods for Ungauged Catchments in France. *Geosciences* 7 (3): 88.

Paquet, E, Garavaglia, F, Garcon, R and Gailhard, J. 2013. The SCHADEX method: A semi-continuous rainfall–runoff simulation for extreme flood estimation. *Journal of Hydrology* 495: 23–37.

Pathiraja, S, Westra, S and Sharma, A. 2012. Why continuous simulation? The role of antecedent moisture in design flood estimation. *Water Resources Research* 48 (6): W06534 (1 - 15).

Pegram, G, Sinclair, S and Bardossy, A. 2016. *New Methods of Infilling Southern African Raingauge Records Enhanced by Annual, Monthly and Daily Precipitation Estimates Tagged with Uncertainty*. WRC Report No. 2241/1/15. Water Research Commission, Pretoria, South Africa.

Perrin, C, Michel, C and Andréassian, V. 2003. Improvement of a parsimonious model for streamflow simulation. *Journal of Hydrology* 279: 275–289.

Pitman, W. 2011. Overview of water resource assessment in South Africa: Current state and future challenges. *Water SA* 37 (5): 659–664.

Rogger, M, Kohl, B, Pirkl, H, Viglione, A, Komma, J, Kirnbauer, R, Merz, R and Blöschl, G. 2012. Runoff models and flood frequency statistics for design flood estimation in Austria – Do they tell a consistent story? *Journal of Hydrology* 456–457: 30–43.

Rossman, L. 2015. *Storm Water Management Model User's Manual Version 5.1*. U.S. Environmental Protection Agency, EPA- 600/R-14/413b, Cincinnati, United States.

Rowe, T. 2015. Development and Assessment of Rules to Parameterise the *ACRU* Model for Design Flood Estimation. Unpublished thesis, Centre for Water Resources Research, University of KwaZulu-Natal, Pietermartizburg, South Africa.

Rowe, T, Smithers, J, Horan, M and Schulze, R. 2018. Development and assessment of rules to parameterise the *ACRU* model for design flood estimation. *Water SA* 44 (1): 93-104.

Royappen, M. 2002. Towards improved parameter estimation in streamflow Predictions using the *ACRU* model. Unpublished thesis, School of Bioresources Engineering and Environmental Hydrology, University of KwaZulu-Natal, Pietermaritzburg, South Africa.

Royappen, M, Dye, P, Schulze, R and Gush, M. 2002. *An analysis of catchment attributes and hydrological response characteristics in a range of small catchments*. WRC Report No. 1193/1/02. Water Research Commission, Pretoria, South Africa.

SANRAL. 2013. *Drainage Manual (Sixth Edition)*. South African National Roads Agency Ltd, Pretoria, South Africa.

Schmidt, E and Schulze, R. 1984. *Improved Estimation of Peak Flow Rates using Modified SCS Lag Equations*. *ACRU* Report No. 17. Department of Agricultural Engineering, University of Natal, Pietermaritzburg, South Africa.

Schmidt, E and Schulze, R. 1987a. *Flood Volume and Peak Discharge from Small Catchments in Southern Africa, Based on the SCS Technique*. WRC Project No. 155 (TT 31/87). Water Research Commission, Pretoria, South Africa.

Schmidt, E and Schulze, R. 1987b. *User Manual for SCS-based design runoff estimation in southern Africa*. WRC-TT 33/87. Water Research Commission, Pretoria, South Africa.

Schmidt, E, Schulze, R and Dent, M. 1987. *Flood Volume and Peak Discharge from Small Catchments in Southern Africa, Based on the SCS Technique: APPENDICES*. WRC Project No. 155 (TT 32/87). Water Research Commission, Pretoria, South Africa.

Schulze, R. 1989. *Non-stationary catchment responses and other problems in determining flood series: A case for a simulation modelling approach. In: Kienzle SW and Maaren H (eds.). Proceedings of the Fourth South African National Hydrological Symposium. SANCIAHS,* Pretoria, South Africa.

Schulze, R. 1995. *Hydrology and Agrohydrology: A Text to Accompany the ACRU 3.00 Agrohydrological Modelling System*. WRC Report No. TT 69/95. Water Research Commission, Pretoria, South Africa.

Schulze, R. 2012. *Mapping hydrological soil groups over South Africa for use with the SCS – SA design hydrograph technique: methodology and results. 16th SANCIAHS National Hydrology Symposium 2012, School of Agricultural, Earth and Environmental Sciences, University of KwaZulu-Natal*. Pietermaritzburg, South Africa.

Schulze, R. 2013. *Modelling Impacts of Land Use on Hydrological Responses in South Africa with the ACRU Model by Sub-Delineation of Quinary Catchments into Land Use Dependent Hydrological Response Units*. Internal Report. School of Agricultural, Earth and Environmental Science, University of KwaZulu-Natal, Pietermaritzburg, South Africa.

Schulze, R, Angus, G, Lynch, S and Smithers, J. 1994. *ACRU: Concepts and Structure*. *ACRU* Theory Manual. University of KwaZulu-Natal, Pietermaritzburg, South Africa.

Schulze, R and Arnold, H. 1979. *Estimation of Volume and Rate of Runoff in Small Catchments in South Africa, Based on the SCS Technique. . ACRU* Report No. 8. Department of Agricultural Engineering, University of Natal, Pietermaritzburg, South Africa.

Schulze, R and Hohls, B. 1993. *A Generic Hydrological Land Cover and Land Use Classification with Decision Support Systems for use in Models*. Proceedings, 6th South African National Hydrology Symposium. University of Natal, Department of Agricultural Engineering, Pietermaritzburg, South Africa.

Schulze, R and Horan, M. 2008. *Soils: Hydrological Attributes. In: Schulze, R (Ed). 2008. South African Atlas of Climatology and Agrohydrology*. WRC Report 1489/1/08. Water Research Commission, Pretoria, South Africa.

Schulze, R and Horan, M. 2010. *Methods 1: Delineation of South Africa, Lesotho and Swaziland into quinary catchments (Chapter 6). In: Schulze RE, Hewitson BC, Barichievy KR, Tadross MA, Kunz RP, Horan MJC and Lumsden TG (eds.). Methodological Approaches to Assessing Eco-Hydrological Responses to Climate Change in South Africa*. WRC Report No. 1562/1/10. Water Research Commission, Pretoria, South Africa. 55-62.

Schulze, R and Kunz, R. 2010. *Climate Change 2010 and Rainfall Seasonality. In: Schulze, R.E. 2010. Atlas of Climate Change and the South African Agricultural Sector: A 2010 Perspective*. Department of Agriculture, Forestry and Fisheries, Pretoria, South Africa.

Schulze, R and Maharaj, M. 2004. *Development of a Database of Gridded Daily Temperatures for Southern Africa*. WRC Report 1156/2/04. Water Research Commission, Pretoria, South Africa.

Schulze, R, Schmidt, E and Smithers, J. 1992. *PC-Based SCS Design Flood Estimates for Small Catchments in Southern Africa*. *ACRU* Report No. 40 - SCS-SA User Manual. Department of Agricultural Engineering, University of Natal, Pietermaritzburg, South Africa.

Schulze, R, Schmidt, E and Smithers, J. 2004. *PC-Based SCS Design Flood Estimates for Small Catchments in Southern Africa*. *ACRU*cons Report No. 52 - Visual SCS-SA User Manual, Version 1. School of Bioresources Engineering and Environmental Hydrology, University of KwaZulu-Natal, Pietermaritzburg, South Africa.

Schulze, R and Schütte, S. 2018. *Mapping SCS Hydrological Soil Groups over South Africa at Terrain Unit Resolution*. Internal Report. School of Agricultural, Earth and Environmental Science, University of KwaZulu-Natal, Pietermaritzburg, South Africa.

Scott, D, Prinsloo, F, Moses, G, Mehlomakulu, M and Simmers, A. 2000. *A Re-analysis of the South African Catchment Afforestation Experimental Data*. WRC Report No. 810/1/00. Water Research Commission, Pretoria, South Africa.

SCS. 1956. *Hydrology National Engineering Handbook, Supplement A, Section 4*. Soil Conservation Service, US Department of Agriculture, Washington, DC, United States.

SCS. 1972. *National Engineering Handbook, Section 4*. Soil Conservation Service, US Department of Agriculture, Washington, DC, United States.

Sharma, A, Srikanthan, R, Mehrotra, R, Westra, S and Lambert, M. 2016. *Rainfall Estimation, Book 2, Chapter 7 - Continuous Rainfall Simulation in Australian Rainfall and Runoff: A Guide to Flood Estimation*. Australian Rainfall and Runoff (ARR), Commonwealth of Australia.

Singh, J, Knapp, H and Demissie, M. 2004. *Hydrologic Modeling of the Iroquois River Watershed Using HSPF and SWAT*. Illinois State Water Survey Contract Report 2004-08, Illinois Department of Natural Resources and Illinois State Geological Survey, Illinois, United States.

SIRI. 1987. *Land Type Series. Memoirs on the Agricultural Natural Resources of South Africa*. Department of Agriculture and Water Supply, Soil and Irrigation Research Institute, Pretoria, South Africa.

Sivapalan, M, Blöschl, G, Merz, R and Gutknecht, D. 2005. Linking flood frequency to long-term water balance: Incorporating effects of seasonality. *Water Resources Research* 41 (6): W06012, 1-17.

Smithers, J. 2012. Review Methods for design flood estimation in South Africa. *Water SA* 38 (4): 633-646.

Smithers, J, Chetty, K, Frezghi, M, Knoesen, D and Tewolde, M. 2007. *Development and Assessment of a Continuous Simulation Modelling System for Design Flood Estimation*. WRC Report No. 1318/1/07. School of Bioresources Engineering and Environmental Hydrology, University of KwaZulu-Natal, Pietermaritzburg, South Africa.

Smithers, J, Chetty, K, Frezghi, M, Knoesen, D and Tewolde, M. 2013. Development and assessment of a daily time-step continuous simulation modelling approach for design flood estimation at ungauged locations: *ACRU* model and Thukela Catchment case study. *Water SA* 30 (4): 467-476.

Smithers, J, Görgens, A, Gericke, J, Jonker, V and Roberts, C. 2016. *The Initiation of a National Flood Studies Programme for South Africa*. South African National Committee on Large Dams (SANCOLD), Pretoria, South Africa.

Smithers, J, Pegram, G and Schulze, R. 2002. Design rainfall estimation in South Africa using Bartlett-Lewis rectangular pulse rainfall models. *Journal of Hydrology* 258 83-89.

Smithers, J and Schulze, R. 1994a. *The Cedara Hydrological Research Catchments 1974 to 1994*. *ACRU* Report No. 42. Department of Agricultural Engineering, University of Natal, Pietermaritzburg, South Africa.

Smithers, J and Schulze, R. 1994b. *The Dehoek/Ntabamhlope Hydrological Research Catchments 1974 to 1994*. *ACRU* Report No. 42. Department of Agricultural Engineering, University of Natal, Pietermaritzburg, South Africa.

Smithers, J and Schulze, R. 2000. *Development and Evaluation of Techniques for Estimating Short Duration Design Rainfall in South Africa*. WRC Report No. 681/1/00. Water Research Commission, Pretoria, South Africa.

Smithers, J and Schulze, R. 2002. *Design Rainfall and Flood Estimation in South Africa*. WRC Project No. K5/1060. WRC Report No. 1060/01/03. Water Research Commission, Pretoria, South Africa. 155 pp.

Smithers, J and Schulze, R. 2004. *ACRU Agrohydrological Modelling System*. User Manual Version 4. School of Bioresources Engineering and Environmental Hydrology, University of KwaZulu-Natal, Pietermaritzburg, South Africa.

Smithers, J, Schulze, R and Kienzle, S. 1997. Design flood estimation using a modelling approach. In: Rosbjerg, D., Boutayeb, N., Gustard, A., Kundzewicz, Z.W., Rasmussen, P.F. (Eds.), Sustainability of water resources under increasing uncertainty. *The International Association of Hydrological Sciences Publication* 240: 365–376.

Smithers, J, Schulze, R and Pegram, G. 2000. Using stochastically generated rainfall series to estimate short duration design rainfalls in South Africa. *Agricultural Engineering in South Africa* 23 (1): 109-113.

Smithers, J, Schulze, R, Pike, A and Jewitt, G. 2001. A hydrological perspective of the February 2000 floods: A case study in the Sabie River catchment. *Water SA* 27 (3): 325-332.

Soong, D, Murphy, E and Straub, T. 2009. *Effect of Detention Basin Release Rates on Flood Flows - Application of a Model to the Blackberry Creek Watershed in Kane County, Illinois*. Virginia, United States.

Soong, D, Straub, T and Murphy, E. 2005. *Continuous Hydrologic Simulation and Flood-Frequency, Hydraulic, and Flood-Hazard Analysis of the Blackberry Creek Watershed, Kane County, Illinois*. U.S. Geological Survey, Virginia, United States.

UNISDR. 2015. *The Human Cost of Weather-Related Disasters 1995-2015*. The United Nations Office for Disaster Risk Reduction (UNISDR) in partnership with The Centre for Research on the Epidemiology of Disasters (CRED), Geneva, Switzerland.

USACE. 2008. *Hydrologic Modeling System HEC-HMS User's Manual Version 3.3*. User's Manual version 3.3. U.S. Army Corps of Engineers Hydrologic Engineering Center (HEC), Davis, CA, United States.

USACE. 2016. *Hydrologic Modeling System HEC-HMS User's Manual Version 4.2*. User's Manual version 4.2. U.S. Army Corps of Engineers Hydrologic Engineering Center (HEC), Davis, CA, United States.

Van Biljon, S. 2000. *Flood Characteristics at Selected Sites and Operation of Reservoirs During the February 2000 Floods. Southern Africa Floods of February 2000*. Depatrment of Civil Engineering, University of Pretoria, Pretoria, South Africa.

Van Bladeren, D and Van der Spuy, D. 2000. *The February 2000 Flood - The Worst in Living Memory? Southern Africa Floods of February 2000*. Depatrment of Civil Engineering, University of Pretoria, Pretoria, South Africa.

van Esse, W, Perrin, C, Booij, M, Augustijn, D, Fenicia, F, Kavetski, D and Lobligeois, F. 2013. The influence of conceptual model structure on model performance: a comparative study for 237 French catchments. *Hydrology and Earth System Sciences* 17: 4227–4239.

van Vuuren, S, van Dijk, M and Coetzee, G. 2013. *Status Review and Requirements of Overhauling Flood Determination Methods in South Africa*. WRC Project No. K8/994 (TT 563/13). Water Research Commission, Pretoria, South Africa.

Vogel, RM. 2017. Stochastic watershed models for hydrologic risk management. *Water Security* 1 28-35.

Weddepohl, J. 1988. Design rainfall distributions for Southern Africa. Unpublished thesis, Department of Agricultural Engineering University of Natal, Pietermaritzburg, South Africa.

Weinmann, P, Rahman, A, Hoang, T, Laurenson, E and Nathan, R. 2002. Monte Carlo simulation of flood frequency curves from rainfall – the way ahead. *Australian Journal of Water Resources* 6 (1): 71-80.

Wessels, P and Rooseboom, A. 2009. Flow-gauging structures in South African rivers Part 1 - An overview. *Water SA* 35 (1): 1-9.

WHS. 2016. *The Revitalised Flood Hydrograph Model ReFH 2.2: Technical Guidance*. Wallingford HydroSolutions Ltd, Wallingford HydroSolutions Ltd, Wallingford, United Kingdom.

WRA. 2018. Water Resource Associates - HYSIM. [Internet]. Water Resource Associates. Available from: http://www.watres.com/software/HYSIM/. [Accessed: 04 May].

Zeng, Q, Chen, H, Xu, C, Jie, M and Hou, Y. 2016. Feasibility and uncertainty of using conceptual rainfall-runoff models in design flood estimation. *Hydrology Research* 47 (4): 701-717.

Zucchini, W, Adamson, P and McNeill, L. 1992. A model of Southern African rainfall. *South African Journal of Science* 88 (2): 103-109.

# 10. APPENDIX A: REVISED SCS-SA CLASSIFICATION AND ASSIGNED *ACRU* LAND COVER CLASSES

Table 10.1 Revised SCS-SA land cover classification and assigned *ACRU* classes

| **Revised SCS Class** | **Treatment / Class Type** | **Hydrological Condition - Representative of Stormflow Potential (SP)** | **Assigned *ACRU* Class (COMPOVEG Number)** |
|---|---|---|---|
| Fallow | 1 = Straight row | - | Agriculture_Commercial_Fallow (Clark, 2015) |
| | 2 = Straight row + conservation tillage | Poor | |
| | 3 = Straight row + conservation tillage | Good | |
| Row Crops | 1 = Straight row | Poor | MAIZE - ALL AREAS = NOV 1GROWING SEASON = 140 days Sabie (3120102) |
| | 2 = Straight row | Good | |
| | 3 = Straight row + conservation tillage | Poor | |
| | 4 = Straight row + conservation tillage | Good | |
| | 5 = Planted on contour | Poor | |
| | 6 = Planted on contour | Good | |
| | 7 = Planted on contour + conservation tillage | Poor | |
| | 8 = Planted on contour + conservation tillage | Good | |
| | 9 = Conservation structures | Poor | |
| | 10 = Conservation structures | Good | |
| | 11 = Conservation structures + conservation tillage | Poor | |
| | 12 = Conservation structures + conservation tillage | Good | |
| Garden Crops | 1 = Straight row | Good | Agriculture_Commercial_Vegetables_Irrigated (Clark, 2015) |
| | 2 = Straight row | Poor | |
| Unimproved (Natural) Grassland | 1 = in poor condition | Poor | DEGRADED UNIMPROVED GRASSLAND (5150102) |
| | 2 = in fair condition | Fair | UNIMPROVED GRASSLAND (5060103) |
| | 3 = in good condition | Good | |
| Improved Grassland (Planted Grassland) | 1 = in poor condition | Poor | IMPROVED GRASS LAND (INLAND) (5070102) |
| | 2 = in fair condition | Fair | |
| | 3 = in good condition | Good | |

Table 10.1 (Continued)

| **Revised SCS Class** | **Treatment / Class Type** | **Hydrological Condition - Representative of Stormflow Potential (SP)** | **Assigned *ACRU* Class (COMPOVEG Number)** |
|---|---|---|---|
| Small Grain | 1 = Straight row | Poor | WHEAT - OFSNATALCAPE= JUN 15= 150 days (3020204) |
| | 2 = Straight row | Good | |
| | 3 = Straight row + conservation tillage | Poor | |
| | 4 = Straight row + conservation tillage | Good | |
| | 5 = Planted on contour | Poor | |
| | 6 = Planted on contour | Good | |
| | 7 = Planted on contour + conservation tillage | Poor | |
| | 8 = Planted on contour + conservation tillage | Good | |
| | 10 = Conservation structures | Poor | |
| | 11 = Conservation structures | Good | |
| | 12 = Conservation structures + conservation tillage | Poor | |
| | 13 = Conservation structures + conservation tillage | Good | |
| Close Seeded Legumes or Rotational Meadow | 1 = Straight Row | Poor | PASTURES - ANNUAL CROP: ryegrass = APR 15 (3021002) |
| | 2 = Straight Row | Good | |
| | 3 = Planted on contour | Poor | |
| | 4 = Planted on contour | Good | |
| | 5 = Conservation structures | Poor | |
| | 6 = Conservation structures | Good | |
| Sugarcane | 1 = Straight row: trash burnt | - | CULTIVATED PERMANENT COMMERCIAL SUGAR CANE (SOUTH COAST) (5200712) |
| | 2 = Straight row: trash mulch | - | |
| | 3 = Straight row: limited cover | - | |
| | 4 = Straight row: partial cover | - | |
| | 5 = Straight row: complete cover | - | |
| | 6 = Conservation structures: limited cover | - | |
| | 7 = Conservation structures: partial cover | - | |
| | 8 = Conservation structures: complete cover | - | |

Table 10.1 (Continued)

| Revised SCS Class | Treatment / Class Type | Hydrological Condition - Representative of Stormflow Potential (SP) | Assigned *ACRU* Class (COMPOVEG Number) |
|---|---|---|---|
| Herbland | 1 = in poor condition | Poor | THE WESTERN MOUNTAIN KAROO (Acocks #28) (2040106) |
| | 2 = in fair condition | Fair | |
| | 3 = in good condition | Good | |
| Shrubland and Low Fynbos | 1 = in poor condition | Poor | KARROID BROKEN VELD (Acocks #26) (2040104) |
| | 2 = in fair condition | Fair | |
| | 3 = in good condition | Good | |
| Pasture | 1 = in poor condition | Poor | PASTURES - PERENNIAL CROP Nymabathi (3021001) |
| | 2 = in fair condition | Fair | |
| | 3 = in good condition | Good | |
| | 4 = Pasture planted on contour | Poor | |
| | 5 = Pasture planted on contour | Fair | |
| | 6 = Pasture planted on contour | Good | |
| Irrigated Pasture | - | Good | CULTIVATED PERMANENT COMMERCIAL IRRIGATED (5181001) |
| Meadow | - | Good | PASTURES - PERENNIAL CROP Nymabathi (3021001) |
| Woodland | 1 = in poor condition | Poor | WOODLAND (Indigenous/Tree-bush savannah) (2010101) |
| | 2 = in fair condition | Fair | |
| | 3 = in good condition | Good | |
| Thicket, Bushland, Bush Clumps, High Fynbos | 1 = in poor condition | Poor | THICKET AND BUSHLAND etc (5030101) |
| | 2 = in fair condition | Fair | |
| | 3 = in good condition | Good | |
| Orchards | 1 = Winter rainfall region, understory of crop cover | - | CITRUS - TVL AND NATAL (3021101) |

Table 10.1 (Continued)

| **Revised SCS Class** | **Treatment / Class Type** | **Hydrological Condition - Representative of Stormflow Potential (SP)** | **Assigned *ACRU* Class (COMPOVEG Number)** |
|---|---|---|---|
| Plantations Clearfelled | Clearfelled | - | Agriculture_Commercial_Fallow (Clark, 2015) |
| Forests & Plantations | Humus depth < 50mm - equivalent to Young trees (1-3 years Gum + Wattle + General; 1-5 years pine): Compactness/site preparation: | compact/Intensive site prep | Natural Forests:<br>FOREST/NATURAL FOREST (5020101)<br>Plantations:<br>Forest_Plantations_General (Clark, 2015) |
| | | Fair/Intermediate site prep | |
| | | loose or friable/Site prep pitting | |
| | Humus depth 50 - 100mm - equivalent to Intermediate trees (4-6 years Gum + Wattle + General; 6-11 years pine): Compactness/site preparation: | compact/Intensive site prep | |
| | | Fair/Intermediate site prep | |
| | | loose or friable/Site prep pitting | |
| | Humus depth > 100mm - equivalent to Mature trees (7-10 years Gum + Wattle + General; 12-16 years pine): Compactness/site preparation: | compact/Intensive site prep | |
| | | Fair/Intermediate site prep | |
| | | loose or friable/Site prep pitting | |
| Urban/Sub-urban Land Cover Classes | 1 = Open spaces, parks, cemeteries | good condition (75% grass cover) | IMPROVED GRASS LAND (INLAND) (5070102) |
| | 2 = Open spaces, parks, cemeteries | fair condition (50-75% grass cover) | |

| **Revised SCS Class** | **Classes with Pervious and Impervious Portions** | **SCS Class for Pervious Portion** | **Impervious Fraction** | **Adjunct Fraction** | **Disjunct Fraction** | **Assigned *ACRU* Class for Pervious Portion (COMPOVEG Number)** |
|---|---|---|---|---|---|---|
| Urban/Sub-urban Land Cover Classes | Urban / Built-up (residential) | Improved Grassland (Planted Grassland) in Fair Condition | 0.65 | 0.5 | 0.15 | IMPROVED GRASS LAND (INLAND) (5070102) |
| | Urban / Built-up (rural cluster) | Unimproved (Natural) Grassland in Poor Condition | 0.1 | 0 | 0.1 | DEGRADED UNIMPROVED GRASSLAND (5150102) |

Table 10.1 (Continued)

| **Revised SCS Class** | **Classes with Pervious and Impervious Portions** | **SCS Class for Pervious Portion** | **Impervious Fraction** | **Adjunct Fraction** | **Disjunct Fraction** | **Assigned *ACRU* Class for Pervious Portion (COMPOVEG Number)** |
|---|---|---|---|---|---|---|
| Urban/Sub-urban Land Cover Classes | Urban / Built-up (residential, formal suburbs) | Improved Grassland (Planted Grassland) in Fair Condition | 0.65 | 0.15 | 0.5 | IMPROVED GRASS LAND (INLAND) (5070102) |
| | Urban / Built-up (residential, flatland) | | 0.65 | 0.5 | 0.15 | |
| | Urban / Built-up (residential, mixed) | | 0.4 | 0.25 | 0.15 | |
| | Urban / Built-up (residential, hostels) | | 0.65 | 0.5 | 0.15 | |
| | Urban / Built-up (residential, formal township) | | 0.65 | 0.15 | 0.5 | |
| | Urban / Built-up (residential, informal township) | Unimproved (Natural) Grassland in Poor Condition | 0.65 | 0.15 | 0.5 | DEGRADED UNIMPROVED GRASSLAND (5150102) |
| | Urban / Built-up (residential, informal squatter camp) | | 0.6 | 0 | 0.6 | |
| | Urban / Built-up (smallholdings, forest & woodland) | Improved Grassland (Planted Grassland) in Fair Condition | 0.05 | 0 | 0.05 | IMPROVED GRASS LAND (INLAND) (5070102) |
| | Urban / Built-up (smallholdings, thicket, bushland) | | 0.05 | 0 | 0.05 | |
| | Urban / Built-up (smallholdings, shrubland) | | 0.05 | 0 | 0.05 | |
| | Urban / Built-up (smallholdings, grassland) | | 0.05 | 0 | 0.05 | |

Table 10.1 (Continued)

| **Revised SCS Class** | **Classes with Pervious and Impervious Portions** | **SCS Class for Pervious Portion** | **Impervious Fraction** | **Adjunct Fraction** | **Disjunct Fraction** | **Assigned *ACRU* Class for Pervious Portion (COMPOVEG Number)** |
|---|---|---|---|---|---|---|
| Urban/Sub-urban Land Cover Classes | Urban / Built-up, (commercial, mercantile) | Improved Grassland (Planted Grassland) in Fair Condition | 0.85 | 0.7 | 0.15 | IMPROVED GRASS LAND (INLAND) (5070102) |
| | Urban / Built-up, (commercial, education, health, IT) | | 0.65 | 0.5 | 0.15 | |
| | Urban / Built-up, (industrial / transport : heavy) | | 0.7 | 0.4 | 0.3 | |
| | Urban / Built-up, (industrial / transport : light) | | 0.5 | 0.3 | 0.2 | |
| Mines and Quarries | Mines & Quarries (underground / subsurface mining) | Unimproved (Natural) Grassland in Poor Condition | 0.8 | 0.5 | 0.3 | DEGRADED UNIMPROVED GRASSLAND (5150102) |
| | Mines & Quarries (surface-based mining) | | 0.8 | 0.5 | 0.3 | |
| | Mines & Quarries (mine tailings, waste dumps) | | 0.8 | 0.5 | 0.3 | |
| Bare Rock and Soil | Bare Rock and Soil (natural) | Unimproved (Natural) Grassland in Poor Condition | 0.85 | 0 | 0.85 | DEGRADED UNIMPROVED GRASSLAND (5150102) |
| | Bare Rock and Soil (erosion : dongas / gullies) | | 0.8 | 0.8 | 0 | |
| | Bare Rock and Soil (erosion : sheet) | | 0.8 | 0.1 | 0.7 | |

NB: For land cover classes with poor and good condition classes, the original *ACRU* class selected, with its default assigned parameters, will be used to represent good condition, however, for poor condition the original *ACRU* class parameters will be changed based on rules developed by Schulze (2013) and Rowe (2015). Similarly, for land cover classes with poor, fair and good condition classes, the original *ACRU* class selected will be used to represent fair condition, however, for poor and good condition the original *ACRU* class variables will be changed based on rules developed by Schulze (2013) and Rowe (2015). The one exception is the Unimproved (natural) Grassland class, where a poor condition or degraded condition class was available from the COMPOVEG database, in which case that class was assigned directly to represent poor condition.

# 11. APPENDIX B: FINAL *ACRU* LAND COVER CLASSIFICATION

Table 11.1 Final land cover classification for use with the *ACRU* CSM system (QF = *QFRESP* and SM = *SMDDEP*)

| **Land Cover Class** | **Treatment / Class Type** | **Hydrological Condition - Representative of Stormflow Potential (SP)** | **SCS Hydrological Soil Groups and *QFRESP* (QF) and *SMDDEP* (SM) Values** | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | **A** | | **A/B** | | **B** | | **B/C** | | **C** | | **C/D** | | **D** | |
| | | | **QF** | **SM** | **QF** | **SM** | **QF** | **SM** | **QF** | **SM** | **QF** | **SM** | **QF** | **SM** | **QF** | **SM** |
| Fallow | 1 = Straight row | - | 0.96 | 0.25 | 1.00 | 0.21 | 1.00 | 0.15 | 1.00 | 0.12 | 1.00 | 0.09 | 1.00 | 0.08 | 1.00 | 0.05 |
| | 2 = Straight row + conservation tillage | Poor | 0.91 | 0.25 | 1.00 | 0.23 | 1.00 | 0.18 | 1.00 | 0.14 | 1.00 | 0.12 | 1.00 | 0.12 | 1.00 | 0.08 |
| | 3 = Straight row + conservation tillage | Good | 0.89 | 0.25 | 1.00 | 0.25 | 1.00 | 0.19 | 1.00 | 0.17 | 1.00 | 0.14 | 1.00 | 0.16 | 1.00 | 0.10 |
| Row Crops | 1 = Straight row | Poor | 0.85 | 0.25 | 0.96 | 0.25 | 1.00 | 0.22 | 1.00 | 0.17 | 1.00 | 0.13 | 1.00 | 0.14 | 1.00 | 0.09 |
| | 2 = Straight row | Good | 0.73 | 0.25 | 0.87 | 0.25 | 0.98 | 0.25 | 1.00 | 0.21 | 1.00 | 0.17 | 1.00 | 0.20 | 1.00 | 0.12 |
| | 3 = Straight row + conservation tillage | Poor | 0.82 | 0.25 | 0.91 | 0.25 | 1.00 | 0.25 | 1.00 | 0.19 | 1.00 | 0.15 | 1.00 | 0.18 | 1.00 | 0.12 |
| | 4 = Straight row + conservation tillage | Good | 0.66 | 0.25 | 0.80 | 0.25 | 0.91 | 0.25 | 1.00 | 0.25 | 1.00 | 0.21 | 0.98 | 0.25 | 1.00 | 0.17 |
| | 5 = Planted on contour | Poor | 0.80 | 0.25 | 0.91 | 0.25 | 1.00 | 0.25 | 1.00 | 0.21 | 1.00 | 0.18 | 1.00 | 0.22 | 1.00 | 0.13 |
| | 6 = Planted on contour | Good | 0.69 | 0.25 | 0.78 | 0.25 | 0.91 | 0.25 | 1.00 | 0.25 | 1.00 | 0.21 | 0.98 | 0.25 | 1.00 | 0.15 |
| | 7 = Planted on contour + conservation tillage | Poor | 0.78 | 0.25 | 0.89 | 0.25 | 0.98 | 0.25 | 1.00 | 0.22 | 1.00 | 0.19 | 1.01 | 0.25 | 1.00 | 0.14 |
| | 8 = Planted on contour + conservation tillage | Good | 0.66 | 0.25 | 0.80 | 0.25 | 0.89 | 0.25 | 0.98 | 0.25 | 1.00 | 0.23 | 0.92 | 0.25 | 1.00 | 0.18 |
| | 9 = Conservation structures | Poor | 0.71 | 0.25 | 0.80 | 0.25 | 0.89 | 0.25 | 0.96 | 0.25 | 1.00 | 0.23 | 0.92 | 0.25 | 1.00 | 0.21 |
| | 10 = Conservation structures | Good | 0.62 | 0.25 | 0.73 | 0.25 | 0.82 | 0.25 | 0.91 | 0.25 | 0.98 | 0.25 | 0.86 | 0.25 | 1.00 | 0.22 |
| | 11 = Conservation structures + conservation tillage | Poor | 0.69 | 0.25 | 0.80 | 0.25 | 0.87 | 0.25 | 0.94 | 0.25 | 1.00 | 0.25 | 0.86 | 0.25 | 1.00 | 0.22 |
| | 12 = Conservation structures + conservation tillage | Good | 0.59 | 0.25 | 0.71 | 0.25 | 0.80 | 0.25 | 0.87 | 0.25 | 0.94 | 0.25 | 0.79 | 0.25 | 1.00 | 0.25 |
| Garden Crops | 1 = Straight row | Good | 0.30 | 0.29 | 0.48 | 0.25 | 0.71 | 0.25 | 0.85 | 0.25 | 0.96 | 0.25 | 0.86 | 0.25 | 1.00 | 0.19 |
| | 2 = Straight row | Poor | 0.75 | 0.25 | 0.82 | 0.25 | 0.91 | 0.25 | 1.00 | 0.25 | 1.00 | 0.22 | 0.95 | 0.25 | 1.00 | 0.18 |
| Unimproved (Natural) Grassland | 1 = in poor condition | Poor | 0.75 | 0.25 | 0.89 | 0.25 | 1.00 | 0.25 | 1.00 | 0.19 | 1.00 | 0.15 | 1.00 | 0.18 | 1.00 | 0.12 |
| | 2 = in fair condition | Fair | 0.32 | 0.25 | 0.59 | 0.25 | 0.78 | 0.25 | 0.91 | 0.25 | 1.00 | 0.25 | 0.92 | 0.25 | 1.00 | 0.18 |
| | 3 = in good condition | Good | 0.30 | 0.37 | 0.37 | 0.25 | 0.59 | 0.25 | 0.75 | 0.25 | 0.89 | 0.25 | 0.79 | 0.25 | 1.00 | 0.23 |
| Improved Grassland (Planted Grassland) | 1 = in poor condition | Poor | 0.75 | 0.25 | 0.89 | 0.25 | 1.00 | 0.25 | 1.00 | 0.19 | 1.00 | 0.15 | 1.00 | 0.18 | 1.00 | 0.12 |
| | 2 = in fair condition | Fair | 0.32 | 0.25 | 0.59 | 0.25 | 0.78 | 0.25 | 0.91 | 0.25 | 1.00 | 0.25 | 0.92 | 0.25 | 1.00 | 0.18 |
| | 3 = in good condition | Good | 0.30 | 0.37 | 0.37 | 0.25 | 0.59 | 0.25 | 0.75 | 0.25 | 0.89 | 0.25 | 0.79 | 0.25 | 1.00 | 0.23 |

Table 11.1 (Continued)

| **Land Cover Class** | **Treatment / Class Type** | **Hydrological Condition - Representative of Stormflow Potential (SP)** | **SCS Hydrological Soil Groups and *QFRESP* (QF) and *SMDDEP* (SM) Values** | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | **A** | | **A/B** | | **B** | | **B/C** | | **C** | | **C/D** | | **D** | |
| | | | **QF** | **SM** | **QF** | **SM** | **QF** | **SM** | **QF** | **SM** | **QF** | **SM** | **QF** | **SM** | **QF** | **SM** |
| Small Grain | 1 = Straight row | Poor | 0.69 | 0.25 | 0.82 | 0.25 | 0.94 | 0.25 | 1.00 | 0.23 | 1.00 | 0.18 | 1.00 | 0.22 | 1.00 | 0.13 |
| | 2 = Straight row | Good | 0.64 | 0.25 | 0.78 | 0.25 | 0.91 | 0.25 | 1.00 | 0.25 | 1.00 | 0.19 | 1.01 | 0.25 | 1.00 | 0.14 |
| | 3 = Straight row + conservation tillage | Poor | 0.66 | 0.25 | 0.80 | 0.25 | 0.89 | 0.25 | 0.98 | 0.25 | 1.00 | 0.21 | 0.98 | 0.25 | 1.00 | 0.15 |
| | 4 = Straight row + conservation tillage | Good | 0.57 | 0.25 | 0.73 | 0.25 | 0.85 | 0.25 | 0.94 | 0.25 | 1.00 | 0.23 | 0.92 | 0.25 | 1.00 | 0.18 |
| | 5 = Planted on contour | Poor | 0.64 | 0.25 | 0.78 | 0.25 | 0.89 | 0.25 | 1.00 | 0.25 | 1.00 | 0.21 | 0.98 | 0.25 | 1.00 | 0.17 |
| | 6 = Planted on contour | Good | 0.59 | 0.25 | 0.73 | 0.25 | 0.87 | 0.25 | 0.98 | 0.25 | 1.00 | 0.22 | 0.95 | 0.25 | 1.00 | 0.18 |
| | 7 = Planted on contour + conservation tillage | Poor | 0.62 | 0.25 | 0.75 | 0.25 | 0.87 | 0.25 | 0.96 | 0.25 | 1.00 | 0.22 | 0.95 | 0.25 | 1.00 | 0.18 |
| | 8 = Planted on contour + conservation tillage | Good | 0.57 | 0.25 | 0.71 | 0.25 | 0.85 | 0.25 | 0.94 | 0.25 | 1.00 | 0.25 | 0.89 | 0.25 | 1.00 | 0.21 |
| | 10 = Conservation structures | Poor | 0.59 | 0.25 | 0.73 | 0.25 | 0.85 | 0.25 | 0.94 | 0.25 | 1.00 | 0.25 | 0.89 | 0.25 | 1.00 | 0.21 |
| | 11 = Conservation structures | Good | 0.55 | 0.25 | 0.69 | 0.25 | 0.80 | 0.25 | 0.91 | 0.25 | 0.98 | 0.25 | 0.86 | 0.25 | 1.00 | 0.22 |
| | 12 = Conservation structures + conservation tillage | Poor | 0.57 | 0.25 | 0.73 | 0.25 | 0.82 | 0.25 | 0.91 | 0.25 | 0.98 | 0.25 | 0.86 | 0.25 | 1.00 | 0.22 |
| | 13 = Conservation structures + conservation tillage | Good | 0.53 | 0.25 | 0.66 | 0.25 | 0.78 | 0.25 | 0.87 | 0.25 | 0.94 | 0.25 | 0.79 | 0.25 | 1.00 | 0.25 |
| Close Seeded Legumes or Rotational Meadow | 1 = Straight Row | Poor | 0.71 | 0.25 | 0.85 | 0.25 | 0.96 | 0.25 | 1.00 | 0.22 | 1.00 | 0.17 | 1.00 | 0.20 | 1.00 | 0.12 |
| | 2 = Straight Row | Good | 0.53 | 0.25 | 0.69 | 0.25 | 0.85 | 0.25 | 0.91 | 0.25 | 1.00 | 0.22 | 0.98 | 0.25 | 1.00 | 0.17 |
| | 3 = Planted on contour | Poor | 0.66 | 0.25 | 0.80 | 0.25 | 0.91 | 0.25 | 1.00 | 0.23 | 1.00 | 0.19 | 0.98 | 0.25 | 1.00 | 0.17 |
| | 4 = Planted on contour | Good | 0.46 | 0.25 | 0.64 | 0.25 | 0.78 | 0.25 | 0.89 | 0.25 | 0.98 | 0.25 | 0.89 | 0.25 | 1.00 | 0.19 |
| | 5 = Conservation structures | Poor | 0.64 | 0.25 | 0.75 | 0.25 | 0.87 | 0.25 | 0.96 | 0.25 | 1.00 | 0.23 | 0.92 | 0.25 | 1.00 | 0.19 |
| | 6 = Conservation structures | Good | 0.37 | 0.25 | 0.57 | 0.25 | 0.73 | 0.25 | 0.85 | 0.25 | 0.94 | 0.25 | 0.79 | 0.25 | 1.00 | 0.23 |
| Sugarcane | 1 = Straight row: trash burnt | - | 0.30 | 0.32 | 0.46 | 0.25 | 0.69 | 0.25 | 0.85 | 0.25 | 0.96 | 0.25 | 0.86 | 0.25 | 1.00 | 0.21 |
| | 2 = Straight row: trash mulch | - | 0.30 | 0.29 | 0.48 | 0.25 | 0.71 | 0.25 | 0.85 | 0.25 | 0.96 | 0.25 | 0.86 | 0.25 | 1.00 | 0.19 |
| | 3 = Straight row: limited cover | - | 0.73 | 0.25 | 0.87 | 0.25 | 0.98 | 0.25 | 1.00 | 0.21 | 1.00 | 0.17 | 1.00 | 0.20 | 1.00 | 0.12 |
| | 4 = Straight row: partial cover | - | 0.32 | 0.25 | 0.57 | 0.25 | 0.78 | 0.25 | 0.87 | 0.25 | 1.00 | 0.25 | 0.92 | 0.25 | 1.00 | 0.18 |
| | 5 = Straight row: complete cover | - | 0.30 | 0.37 | 0.34 | 0.25 | 0.59 | 0.25 | 0.75 | 0.25 | 0.89 | 0.25 | 0.79 | 0.25 | 1.00 | 0.23 |
| | 6 = Conservation structures: limited cover | - | 0.69 | 0.25 | 0.80 | 0.25 | 0.91 | 0.25 | 1.00 | 0.25 | 1.00 | 0.21 | 0.98 | 0.25 | 1.00 | 0.15 |
| | 7 = Conservation structures: partial cover | - | 0.30 | 0.56 | 0.30 | 0.28 | 0.55 | 0.25 | 0.73 | 0.25 | 0.91 | 0.25 | 0.86 | 0.25 | 1.00 | 0.19 |
| | 8 = Conservation structures: complete cover | - | 0.30 | 0.81 | 0.30 | 0.70 | 0.30 | 0.42 | 0.55 | 0.25 | 0.80 | 0.25 | 0.70 | 0.25 | 1.00 | 0.25 |

Table 11.1 (Continued)

| **Land Cover Class** | **Treatment / Class Type** | **Hydrological Condition - Representative of Stormflow Potential (SP)** | **SCS Hydrological Soil Groups and *QFRESP* (QF) and *SMDDEP* (SM) Values** | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | **A** | | **A/B** | | **B** | | **B/C** | | **C** | | **C/D** | | **D** | |
| | | | **QF** | **SM** | **QF** | **SM** | **QF** | **SM** | **QF** | **SM** | **QF** | **SM** | **QF** | **SM** | **QF** | **SM** |
| Herbland | 1 = in poor condition | Poor | 0.75 | 0.25 | 0.89 | 0.25 | 1.00 | 0.25 | 1.00 | 0.19 | 1.00 | 0.15 | 1.00 | 0.18 | 1.00 | 0.12 |
| | 2 = in fair condition | Fair | 0.32 | 0.25 | 0.59 | 0.25 | 0.78 | 0.25 | 0.91 | 0.25 | 1.00 | 0.25 | 0.92 | 0.25 | 1.00 | 0.18 |
| | 3 = in good condition | Good | 0.30 | 0.37 | 0.37 | 0.25 | 0.59 | 0.25 | 0.75 | 0.25 | 0.89 | 0.25 | 0.79 | 0.25 | 1.00 | 0.23 |
| Shrubland and Low Fynbos | 1 = in poor condition | Poor | 0.75 | 0.25 | 0.89 | 0.25 | 1.00 | 0.25 | 1.00 | 0.19 | 1.00 | 0.15 | 1.00 | 0.18 | 1.00 | 0.12 |
| | 2 = in fair condition | Fair | 0.32 | 0.25 | 0.59 | 0.25 | 0.78 | 0.25 | 0.91 | 0.25 | 1.00 | 0.25 | 0.92 | 0.25 | 1.00 | 0.18 |
| | 3 = in good condition | Good | 0.30 | 0.37 | 0.37 | 0.25 | 0.59 | 0.25 | 0.75 | 0.25 | 0.89 | 0.25 | 0.79 | 0.25 | 1.00 | 0.23 |
| Pasture | 1 = in poor condition | Poor | 0.75 | 0.25 | 0.89 | 0.25 | 1.00 | 0.25 | 1.00 | 0.19 | 1.00 | 0.15 | 1.00 | 0.18 | 1.00 | 0.12 |
| | 2 = in fair condition | Fair | 0.32 | 0.25 | 0.59 | 0.25 | 0.78 | 0.25 | 0.91 | 0.25 | 1.00 | 0.25 | 0.92 | 0.25 | 1.00 | 0.18 |
| | 3 = in good condition | Good | 0.30 | 0.37 | 0.37 | 0.25 | 0.59 | 0.25 | 0.75 | 0.25 | 0.89 | 0.25 | 0.79 | 0.25 | 1.00 | 0.23 |
| | 4 = Pasture planted on contour | Poor | 0.30 | 0.26 | 0.50 | 0.25 | 0.73 | 0.25 | 0.91 | 0.25 | 1.00 | 0.22 | 1.01 | 0.25 | 1.00 | 0.13 |
| | 5 = Pasture planted on contour | Fair | 0.30 | 0.56 | 0.30 | 0.28 | 0.55 | 0.25 | 0.73 | 0.25 | 0.91 | 0.25 | 0.86 | 0.25 | 1.00 | 0.19 |
| | 6 = Pasture planted on contour | Good | 0.30 | 0.81 | 0.30 | 0.70 | 0.30 | 0.42 | 0.55 | 0.25 | 0.80 | 0.25 | 0.70 | 0.25 | 1.00 | 0.25 |
| Irrigated Pasture | - | Good | 0.30 | 0.42 | 0.30 | 0.34 | 0.30 | 0.25 | 0.50 | 0.25 | 0.69 | 0.25 | 0.49 | 0.25 | 0.80 | 0.25 |
| Meadow | - | Good | 0.30 | 0.49 | 0.30 | 0.29 | 0.53 | 0.25 | 0.69 | 0.25 | 0.82 | 0.25 | 0.70 | 0.25 | 1.00 | 0.22 |
| Woodland | 1 = in poor condition | Poor | 0.30 | 0.29 | 0.48 | 0.25 | 0.71 | 0.25 | 0.85 | 0.25 | 0.96 | 0.25 | 0.86 | 0.25 | 1.00 | 0.19 |
| | 2 = in fair condition | Fair | 0.30 | 0.41 | 0.32 | 0.25 | 0.57 | 0.25 | 0.75 | 0.25 | 0.87 | 0.25 | 0.76 | 0.25 | 1.00 | 0.25 |
| | 3 = in good condition | Good | 0.30 | 0.56 | 0.30 | 0.26 | 0.46 | 0.25 | 0.66 | 0.25 | 0.80 | 0.25 | 0.67 | 0.25 | 0.96 | 0.25 |
| Thicket, Bushland, Bush Clumps, High Fynbos | 1 = in poor condition | Poor | 0.30 | 0.29 | 0.48 | 0.25 | 0.71 | 0.25 | 0.85 | 0.25 | 0.96 | 0.25 | 0.86 | 0.25 | 1.00 | 0.19 |
| | 2 = in fair condition | Fair | 0.30 | 0.41 | 0.32 | 0.25 | 0.57 | 0.25 | 0.75 | 0.25 | 0.87 | 0.25 | 0.76 | 0.25 | 1.00 | 0.25 |
| | 3 = in good condition | Good | 0.30 | 0.56 | 0.30 | 0.26 | 0.46 | 0.25 | 0.66 | 0.25 | 0.80 | 0.25 | 0.67 | 0.25 | 0.96 | 0.25 |
| Orchards | 1 = Winter rainfall region, understory of crop cover | - | 0.30 | 0.37 | 0.30 | 0.30 | 0.41 | 0.25 | 0.59 | 0.25 | 0.71 | 0.25 | 0.52 | 0.25 | 0.82 | 0.25 |

Table 11.1 (Continued)

| **Land Cover Class** | **Treatment / Class Type** | **Hydrological Condition - Representative of Stormflow Potential (SP)** | **SCS Hydrological Soil Groups and *QFRESP* (QF) and *SMDDEP* (SM) Values** | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | **A** | | **A/B** | | **B** | | **B/C** | | **C** | | **C/D** | | **D** | |
| | | | **QF** | **SM** | **QF** | **SM** | **QF** | **SM** | **QF** | **SM** | **QF** | **SM** | **QF** | **SM** | **QF** | **SM** |
| Plantations Clearfelled | Clearfelled | - | 0.96 | 0.25 | 1.00 | 0.21 | 1.00 | 0.15 | 1.00 | 0.12 | 1.00 | 0.09 | 1.00 | 0.08 | 1.00 | 0.05 |
| Forests & Plantations | Humus depth < 50mm - equivalent to Young trees (1-3 years Gum + Wattle + General; 1-5 years pine): Compactness/site preparation: | compact/Intensive site prep | 0.39 | 0.25 | 0.62 | 0.25 | 0.85 | 0.25 | 0.96 | 0.25 | 1.00 | 0.21 | 1.01 | 0.25 | 1.00 | 0.14 |
| | | Fair/Intermediate site prep | 0.30 | 0.25 | 0.53 | 0.25 | 0.75 | 0.25 | 0.87 | 0.25 | 0.98 | 0.25 | 0.92 | 0.25 | 1.00 | 0.17 |
| | | loose or friable/Site prep pitting | 0.30 | 0.40 | 0.32 | 0.25 | 0.57 | 0.25 | 0.71 | 0.25 | 0.82 | 0.25 | 0.67 | 0.25 | 0.96 | 0.25 |
| | Humus depth 50 - 100mm - equivalent to Intermediate trees (4-6 years Gum + Wattle + General; 6-11 years pine): Compactness/site preparation: | compact/Intensive site prep | 0.30 | 0.30 | 0.47 | 0.25 | 0.71 | 0.25 | 0.82 | 0.25 | 0.94 | 0.25 | 0.84 | 0.25 | 1.00 | 0.20 |
| | | Fair/Intermediate site prep | 0.30 | 0.38 | 0.36 | 0.25 | 0.62 | 0.25 | 0.73 | 0.25 | 0.85 | 0.25 | 0.70 | 0.25 | 0.98 | 0.25 |
| | | loose or friable/Site prep pitting | 0.30 | 0.52 | 0.30 | 0.34 | 0.42 | 0.25 | 0.55 | 0.25 | 0.66 | 0.25 | 0.48 | 0.25 | 0.81 | 0.25 |
| | Humus depth > 100mm - equivalent to Mature trees (7-10 years Gum + Wattle + General; 12-16 years pine): Compactness/site preparation: | compact/Intensive site prep | 0.30 | 0.40 | 0.32 | 0.25 | 0.57 | 0.25 | 0.71 | 0.25 | 0.82 | 0.25 | 0.67 | 0.25 | 0.96 | 0.25 |
| | | Fair/Intermediate site prep | 0.30 | 0.49 | 0.30 | 0.32 | 0.48 | 0.25 | 0.59 | 0.25 | 0.71 | 0.25 | 0.52 | 0.25 | 0.85 | 0.25 |
| | | loose or friable/Site prep pitting | 0.30 | 0.65 | 0.30 | 0.45 | 0.30 | 0.26 | 0.39 | 0.25 | 0.50 | 0.25 | 0.30 | 0.26 | 0.69 | 0.25 |
| Urban/Sub-urban Land Cover Classes | 1 = Open spaces, parks, cemeteries | good condition (75% grass cover) | 0.30 | 0.37 | 0.37 | 0.25 | 0.59 | 0.25 | 0.75 | 0.25 | 0.89 | 0.25 | 0.79 | 0.25 | 1.00 | 0.23 |
| | 2 = Open spaces, parks, cemeteries | fair condition (50-75% grass cover) | 0.32 | 0.25 | 0.59 | 0.25 | 0.78 | 0.25 | 0.91 | 0.25 | 1.00 | 0.25 | 0.92 | 0.25 | 1.00 | 0.18 |

| **Land Cover Class** | **Classes with Pervious and Impervious Portions** | **Class for Pervious Portion** | **Impervious Fraction** | **Adjunct Fraction** | **Disjunct Fraction** | **SCS Hydrological Soil Groups and QF and SM Values - Pervious Portions** | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | **A** | | **A/B** | | **B** | | **B/C** | | **C** | | **C/D** | | **D** | |
| | | | | | | **QF** | **SM** | **QF** | **SM** | **QF** | **SM** | **QF** | **QF** | **SM** | **QF** | **SM** | **QF** | **SM** | **QF** |
| Urban/Sub-urban Land Cover Classes | Urban / Built-up (residential) | Improved Grassland (Planted Grassland) in Fair Condition | 0.65 | 0.5 | 0.15 | 0.32 | 0.25 | 0.59 | 0.25 | 0.78 | 0.25 | 0.91 | 0.25 | 1.00 | 0.25 | 0.92 | 0.25 | 1.00 | 0.18 |
| | Urban / Built-up (rural cluster) | Unimproved (Natural) Grassland in Poor Condition | 0.1 | 0 | 0.1 | 0.75 | 0.25 | 0.89 | 0.25 | 1.00 | 0.25 | 1.00 | 0.19 | 1.00 | 0.15 | 1.00 | 0.18 | 1.00 | 0.12 |

Table 11.1 (Continued)

| **Land Cover Class** | **Classes with Pervious and Impervious Portions** | **Class for Pervious Portion** | **Impervious Fraction** | **Adjunct Fraction** | **Disjunct Fraction** | **SCS Hydrological Soil Groups and QF and SM Values - Pervious Portions** | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | **A** | | **A/B** | | **B** | | **B/C** | | **C** | | **C/D** | | **D** | |
| | | | | | | **QF** | **SM** | **QF** | **SM** | **QF** | **SM** | **QF** | **QF** | **SM** | **QF** | **SM** | **QF** | **SM** | **QF** |
| Urban/Sub-urban Land Cover Classes | Urban / Built-up (residential, formal suburbs) | Improved Grassland (Planted Grassland) in Fair Condition | 0.65 | 0.15 | 0.5 | 0.32 | 0.25 | 0.59 | 0.25 | 0.78 | 0.25 | 0.91 | 0.25 | 1.00 | 0.25 | 0.92 | 0.25 | 1.00 | 0.18 |
| | Urban / Built-up (residential, flatland) | | 0.65 | 0.5 | 0.15 | | | | | | | | | | | | | | |
| | Urban / Built-up (residential, mixed) | | 0.4 | 0.25 | 0.15 | | | | | | | | | | | | | | |
| | Urban / Built-up (residential) | | 0.65 | 0.5 | 0.15 | | | | | | | | | | | | | | |
| | Urban / Built-up (residential, hostels) | | 0.65 | 0.5 | 0.15 | | | | | | | | | | | | | | |
| | Urban / Built-up (residential, formal township) | | 0.65 | 0.15 | 0.5 | | | | | | | | | | | | | | |
| | Urban / Built-up (residential, informal township) | Unimproved (Natural) Grassland in Poor Condition | 0.65 | 0.15 | 0.5 | 0.75 | 0.25 | 0.89 | 0.25 | 1.00 | 0.25 | 1.00 | 0.19 | 1.00 | 0.15 | 1.00 | 0.18 | 1.00 | 0.12 |
| | Urban / Built-up (residential, informal squatter camp) | | 0.6 | 0 | 0.6 | | | | | | | | | | | | | | |
| | Urban / Built-up (smallholdings, forest & woodland) | Improved Grassland (Planted Grassland) in Fair Condition | 0.05 | 0 | 0.05 | 0.32 | 0.25 | 0.59 | 0.25 | 0.78 | 0.25 | 0.91 | 0.25 | 1.00 | 0.25 | 0.92 | 0.25 | 1.00 | 0.18 |
| | Urban / Built-up (smallholdings, thicket, bushland) | | 0.05 | 0 | 0.05 | | | | | | | | | | | | | | |
| | Urban / Built-up (smallholdings, shrubland) | | 0.05 | 0 | 0.05 | | | | | | | | | | | | | | |
| | Urban / Built-up (smallholdings, grassland) | | 0.05 | 0 | 0.05 | | | | | | | | | | | | | | |
| | Urban / Built-up, (commercial, mercantile) | | 0.85 | 0.7 | 0.15 | | | | | | | | | | | | | | |

Table 11.1 (Continued)

| Land Cover Class | Classes with Pervious and Impervious Portions | Class for Pervious Portion | Impervious Fraction | Adjunct Fraction | Disjunct Fraction | SCS Hydrological Soil Groups and QF and SM Values - Pervious Portions | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | A | | A/B | | B | | B/C | | C | | C/D | | D | |
| | | | | | | QF | SM | QF | SM | QF | SM | QF | QF | SM | QF | SM | QF | SM | QF |
| Urban/Sub-urban Land Cover Classes | Urban / Built-up, (commercial, education, health, IT) | Improved Grassland (Planted Grassland) in Fair Condition | 0.65 | 0.5 | 0.15 | 0.32 | 0.25 | 0.59 | 0.25 | 0.78 | 0.25 | 0.91 | 0.25 | 1.00 | 0.25 | 0.92 | 0.25 | 1.00 | 0.18 |
| | Urban / Built-up, (industrial / transport : heavy) | | 0.7 | 0.4 | 0.3 | | | | | | | | | | | | | | |
| | Urban / Built-up, (industrial / transport : light) | | 0.5 | 0.3 | 0.2 | | | | | | | | | | | | | | |
| Mines and Quarries | Mines & Quarries (underground / subsurface mining) | Unimproved (Natural) Grassland in Poor Condition | 0.8 | 0.5 | 0.3 | 0.75 | 0.25 | 0.89 | 0.25 | 1.00 | 0.25 | 1.00 | 0.19 | 1.00 | 0.15 | 1.00 | 0.18 | 1.00 | 0.12 |
| | Mines & Quarries (surface-based mining) | | 0.8 | 0.5 | 0.3 | | | | | | | | | | | | | | |
| | Mines & Quarries (mine tailings, waste dumps) | | 0.8 | 0.5 | 0.3 | | | | | | | | | | | | | | |
| Bare Rock and Soil | Bare Rock and Soil (natural) | Unimproved (Natural) Grassland in Poor Condition | 0.85 | 0 | 0.85 | 0.75 | 0.25 | 0.89 | 0.25 | 1.00 | 0.25 | 1.00 | 0.19 | 1.00 | 0.15 | 1.00 | 0.18 | 1.00 | 0.12 |
| | Bare Rock and Soil (erosion : dongas / gullies) | | 0.8 | 0.8 | 0 | | | | | | | | | | | | | | |
| | Bare Rock and Soil (erosion : sheet) | | 0.8 | 0.1 | 0.7 | | | | | | | | | | | | | | |

NB: For land cover classes with poor and good condition classes, the original *ACRU* class selected, with its default assigned parameters, will be used to represent good condition, however, for poor condition the original *ACRU* class parameters will be changed based on rules developed by Schulze (2013) and Rowe (2015). Similarly, for land cover classes with poor, fair and good condition classes, the original *ACRU* class selected will be used to represent fair condition, however, for poor and good condition the original *ACRU* class variables will be changed based on rules developed by Schulze (2013) and Rowe (2015). The one exception is the Unimproved (natural) Grassland class, where a poor condition or degraded condition class was available from the COMPOVEG database, in which case that class was assigned directly to represent poor condition.

# 12. APPENDIX C: MAPPING *ACRU* LAND COVER CLASSES TO NLC 2000

Table 12.1 Default final *ACRU* land cover classes assigned to the 49 class classification of the NLC 2000 database

| NLC 2000 | | Default Assigned Final *ACRU* Land Cover Class | | |
|---|---|---|---|---|
| **No.** | **Description** | **Land Cover Class** | **Treatment / Class Type** | **Hydrological Condition** |
| 0 | Missing Data | Unimproved (Natural) Grassland | 2 = in fair condition | Fair |
| 1 | Forest (Indigenous) | Forests & Plantations | Humus depth 50 - 100mm - equivalent to Intermediate trees (4-6 years Gum + Wattle + General; 6-11 years pine): Compactness/site preparation: | Fair/Intermediate site preparation |
| 2 | Woodland (previously termed Forest and Woodland) | Woodland | 2 = in fair condition | Fair |
| 3 | Thicket, Bushland, Bush Clumps, High Fynbos | Thicket, Bushland, Bush Clumps, High Fynbos | 2 = in fair condition | Fair |
| 4 | Shrubland and Low Fynbos | Shrubland and Low Fynbos | 2 = in fair condition | Fair |
| 5 | Herbland | Herbland | 2 = in fair condition | Fair |
| 6 | Unimproved (natural) Grassland | Unimproved (Natural) Grassland | 2 = in fair condition | Fair |
| 7 | Improved Grassland (Planted Grassland) | Improved Grassland (Planted Grassland) | 2 = in fair condition | Fair |
| 8 | Forest Plantations (Eucalyptus spp) | Forests & Plantations | Humus depth 50 - 100mm - equivalent to Intermediate trees (4-6 years Gum + Wattle + General; 6-11 years pine): Compactness/site preparation: | Fair/Intermediate site preparation |
| 9 | Forest Plantations (Pine spp) | | | |
| 10 | Forest Plantations (Acacia spp) | | | |
| 11 | Forest Plantations (Other / mixed spp) | | | |
| 12 | Forest Plantations (clearfelled) | | | |
| 13 | Water bodies | Modelled as dams with specified rules | | |
| 14 | Wetlands | Modelled as shallow dam with specified rules | | |
| 15 | Bare Rock and Soil (natural) | Bare Rock and Soil (natural) | - | - |
| 16 | Bare Rock and Soil (erosion : dongas / gullies) | Bare Rock and Soil (erosion : dongas / gullies) | - | - |
| 17 | Bare Rock and Soil (erosion : sheet) | Bare Rock and Soil (erosion : sheet) | - | - |
| 18 | Degraded Forest & Woodland | Woodland | 1 = in poor condition | Poor |
| 19 | Degraded Thicket, Bushland, etc | Thicket, Bushland, Bush Clumps, High Fynbos | 1 = in poor condition | Poor |

Table 12.1 (Continued)

| **NLC 2000** | | **Default Assigned Final *ACRU* Land Cover Class** | | |
|---|---|---|---|---|
| **No.** | **Description** | **Land Cover Class** | **Treatment / Class Type** | **Hydrological Condition** |
| 20 | Degraded Shrubland and Low Fynbos | Shrubland and Low Fynbos | 1 = in poor condition | Poor |
| 21 | Degraded herbland (no areas in NLC_2000 map) | Herbland | 1 = in poor condition | Poor |
| 22 | Degraded Unimproved (natural) Grassland | Unimproved (Natural) Grassland | 1 = in poor condition | Poor |
| 23 | Cultivated, permanent, commercial, irrigated | Irrigated Pasture | - | Good |
| 24 | Cultivated, permanent, commercial, dryland | Pasture | 2 = in fair condition | Fair |
| 25 | Cultivated, permanent, commercial, sugarcane | Sugarcane | 7 = Conservation structures: partial cover | - |
| 26 | Cultivated, temporary, commercial, irrigated | Row Crop (Summer rainfall zones)<br>Small Grain (Winter and all year rainfall zones) | 6 = Planted on contour | Good |
| 27 | Cultivated, temporary, commercial, dryland | Row Crop (Summer rainfall zones)<br>Small Grain (Winter and all year rainfall zones) | 6 = Planted on contour | Good |
| 28 | Cultivated, temporary, subsistence, dryland | Row Crop (Summer rainfall zones)<br>Small Grain (Winter and all year rainfall zones) | 3 = Straight row + conservation tillage | Poor |
| 29 | Cultivated, temporary, subsistence, irrigated | Row Crop (Summer rainfall zones)<br>Small Grain (Winter and all year rainfall zones) | 4 = Straight row + conservation tillage | Good |
| 30 | Urban / Built-up (residential) | Urban / Built-up (residential) | - | - |
| 31 | Urban / Built-up (rural cluster) | Urban / Built-up (rural cluster) | - | - |
| 32 | Urban / Built-up (residential, formal suburbs) | Urban / Built-up (residential, formal suburbs) | - | - |
| 33 | Urban / Built-up (residential, flatland) | Urban / Built-up (residential, flatland) | - | - |
| 34 | Urban / Built-up (residential, mixed) | Urban / Built-up (residential, mixed) | - | - |
| 35 | Urban / Built-up (residential, hostels) | Urban / Built-up (residential, hostels) | - | - |
| 36 | Urban / Built-up (residential, formal township) | Urban / Built-up (residential, formal township) | - | - |
| 37 | Urban / Built-up (residential, informal township) | Urban / Built-up (residential, informal township) | - | - |

Table 12.1 (Continued)

| **NLC 2000** | | **Default Assigned Final *ACRU* Land Cover Class** | | |
|---|---|---|---|---|
| **No.** | **Description** | **Land Cover Class** | **Treatment / Class Type** | **Hydrological Condition** |
| 38 | Urban / Built-up (residential, informal squatter camp) | Urban / Built-up (residential, informal squatter camp) | - | - |
| 39 | Urban / Built-up (smallholdings, forest & woodland) | Urban / Built-up (smallholdings, forest & woodland) | - | - |
| 40 | Urban / Built-up (smallholdings, thicket, bushland) | Urban / Built-up (smallholdings, thicket, bushland) | - | - |
| 41 | Urban / Built-up (smallholdings, shrubland) | Urban / Built-up (smallholdings, shrubland) | - | - |
| 42 | Urban / Built-up (smallholdings, grassland) | Urban / Built-up (smallholdings, grassland) | - | - |
| 43 | Urban / Built-up, (commercial, mercantile) | Urban / Built-up, (commercial, mercantile) | - | - |
| 44 | Urban / Built-up, (commercial, education, health, IT) | Urban / Built-up, (commercial, education, health, IT) | - | - |
| 45 | Urban / Built-up, (industrial / transport : heavy) | Urban / Built-up, (industrial / transport : heavy) | - | - |
| 46 | Urban / Built-up, (industrial / transport : light) | Urban / Built-up, (industrial / transport : light) | - | - |
| 47 | Mines & Quarries (underground / subsurface mining) | Mines & Quarries (underground / subsurface mining) | - | - |
| 48 | Mines & Quarries (surface-based mining) | Mines & Quarries (surface-based mining) | - | - |
| 49 | Mines & Quarries (mine tailings, waste dumps) | Mines & Quarries (mine tailings, waste dumps) | - | - |

# 13. APPENDIX D: MAPPING *ACRU* LAND COVER CLASSES TO NLC 2013/2014

Table 13.1 Default final *ACRU* land cover classes assigned to the 72 class classification of the NLC 2013/2014 database

| NLC 2013/2014 | | Default Assigned Final *ACRU* Land Cover Class | | |
|---|---|---|---|---|
| **No.** | **Description** | **Land Cover Class** | **Treatment / Class Type** | **Hydrological Condition** |
| 0 | Missing Data | Unimproved (Natural) Grassland | 2 = in fair condition | Fair |
| 1 | Water seasonal | Modelled as shallow dam with specified rules | | |
| 2 | Water permanent | Modelled as dams with specified rules | | |
| 3 | Wetlands | Modelled as shallow dam with specified rules | | |
| 4 | Indigenous Forest | Forests & Plantations | Humus depth 50 - 100mm - equivalent to Intermediate trees (4-6 years Gum + Wattle + General; 6-11 years pine): Compactness/site preparation: | Fair/Intermediate site preparation |
| 5 | Thicket /Dense bush | Thicket, Bushland, Bush Clumps, High Fynbos | 2 = in fair condition | Fair |
| 6 | Woodland/Open bush | Woodland | 2 = in fair condition | Fair |
| 7 | Grassland | Unimproved (Natural) Grassland | 2 = in fair condition | Fair |
| 8 | Shrubland fynbos | Shrubland and Low Fynbos | 2 = in fair condition | Fair |
| 9 | Low shrubland | Shrubland and Low Fynbos | 2 = in fair condition | Fair |
| 10 | Cultivated commercial fields (high yield) | Row Crop (Summer rainfall zones)<br>Small Grain (Winter and all year rainfall zones) | 6 = Planted on contour | Good |
| 11 | Cultivated commercial fields (med yield) | | | |
| 12 | Cultivated commercial fields (low yield) | Pasture | 2 = in fair condition | Fair |
| 13 | Cultivated commercial pivots (high yield) | Row Crop (Summer rainfall zones)<br>Small Grain (Winter and all year rainfall zones) | 6 = Planted on contour | Good |
| 14 | Cultivated commercial pivots (med yield) | | | |
| 15 | Cultivated commercial pivots (low yield) | Irrigated Pasture | - | Good |

Table 13.1 (Continued)

| **NLC 2013/2014** | | **Default Assigned Final *ACRU* Land Cover Class** | | |
|---|---|---|---|---|
| **No.** | **Description** | **Land Cover Class** | **Treatment / Class Type** | **Hydrological Condition** |
| 16 | Cultivated orchards (high yield) | Orchards | 1 = Winter rainfall region, understory of crop cover | - |
| 17 | Cultivated orchards (med yield) | | | |
| 18 | Cultivated orchards (low yield) | | | |
| 19 | Cultivated vines (high yield) | | | |
| 20 | Cultivated vines (med yield) | | | |
| 21 | Cultivated vines (low yield) | | | |
| | Cultivated permanent pineapple | Garden Crops | 1 = Straight row | Good |
| 23 | Cultivated subsistence (high yield) | Row Crop (Summer rainfall zones) Small Grain (Winter and all year rainfall zones) | 3 = Straight row + conservation tillage | Poor |
| 24 | Cultivated subsistence (med yield) | | | |
| 25 | Cultivated subsistence (low yield) | Pasture | 3 = in poor condition | Poor |
| 26 | Cultivated cane pivot - crop | Sugarcane | 7 = Conservation structures: partial cover | |
| 27 | Cultivated cane pivot - fallow | | | |
| 28 | Cultivated cane commercial - crop | | | |
| 29 | Cultivated cane commercial - fallow | | | |
| 30 | Cultivated cane emerging - crop | | | |
| 31 | Cultivated cane emerging - fallow | | | |

Table 13.1 (Continued)

| NLC 2013/2014 | | Default Assigned Final *ACRU* Land Cover Class | | |
|---|---|---|---|---|
| **No.** | **Description** | **Land Cover Class** | **Treatment / Class Type** | **Hydrological Condition** |
| 32 | Plantations / Woodlots mature | Forests & Plantations | Humus depth 50 - 100mm - equivalent to Intermediate trees (4-6 years Gum + Wattle + General; 6-11 years pine): Compactness/site preparation: | Fair/Intermediate site preparation |
| 33 | Plantation / Woodlots young | | | |
| 34 | Plantation / Woodlots clearfelled | | | |
| 35 | Mines 1 bare | Mines & Quarries (surface-based mining) | - | - |
| 36 | Mines 2 semi-bare | | | |
| 37 | Mines water seasonal | Modelled as shallow dam with specified rules | | |
| 38 | Mines water permanent | Modelled as shallow dam with specified rules | | |
| 39 | Mine buildings | Mines & Quarries (surface-based mining) | - | - |
| 40 | Erosion (donga) | Bare Rock and Soil (erosion : dongas / gullies) | - | - |
| 41 | Bare none vegetated | Bare Rock and Soil (natural) | - | - |
| 42 | Urban commercial | Urban / Built-up, (commercial, mercantile) | - | - |
| 43 | Urban industrial | | | |
| 44 | Urban informal (dense trees / bush) | Urban / Built-up (residential, informal township) | - | - |
| 45 | Urban informal (open trees / bush) | | | |
| 46 | Urban informal (low veg / grass) | | | |
| 47 | Urban informal (bare) | | | |
| 48 | Urban residential (dense trees / bush) | Urban / Built-up (residential, formal suburbs) | - | - |
| 49 | Urban residential (open trees / bush) | | | |

Table 13.1 (Continued)

| **NLC 2013/2014** | | **Default Assigned Final *ACRU* Land Cover Class** | | |
|---|---|---|---|---|
| **No.** | **Description** | **Land Cover Class** | **Treatment / Class Type** | **Hydrological Condition** |
| 50 | Urban residential (low veg / grass) | Urban / Built-up (residential, formal suburbs) | - | - |
| 51 | Urban residential (bare) | | | |
| 52 | Urban school and sports ground | Urban / Built-up, (commercial, education, health, IT) | - | - |
| 53 | Urban smallholding (dense trees / bush) | Urban / Built-up (smallholdings, thicket, bushland) | - | - |
| 54 | Urban smallholding (open trees / bush) | | | |
| 55 | Urban smallholding (low veg / grass) | Urban / Built-up (smallholdings, grassland) | - | - |
| 56 | Urban smallholding (bare) | | | |
| 57 | Urban sports and golf (dense tree / bush) | Urban / Built-up (smallholdings, thicket, bushland) | - | - |
| 58 | Urban sports and golf (open tree / bush) | | | |
| 59 | Urban sports and golf (low veg / grass) | Urban / Built-up (smallholdings, grassland) | - | - |
| 60 | Urban sports and golf (bare) | | | |
| 61 | Urban township (dense trees / bush) | Urban / Built-up (residential, formal township) | - | - |
| 62 | Urban township (open trees / bush) | | | |
| 63 | Urban township (low veg / grass) | | | |
| 64 | Urban township (bare) | | | |
| 65 | Urban village (dense trees / bush) | Urban / Built-up (residential, mixed) | - | - |
| 66 | Urban village (open trees / bush) | | | |

Table 13.1 (Continued)

| NLC 2013/2014 | | Default Assigned Final *ACRU* Land Cover Class | | |
|---|---|---|---|---|
| **No.** | **Description** | **Land Cover Class** | **Treatment / Class Type** | **Hydrological Condition** |
| 67 | Urban village (low veg / grass) | Urban / Built-up (residential, mixed) | - | - |
| 68 | Urban village (bare) | | | |
| 69 | Urban built-up (dense trees / bush) | Urban / Built-up, (commercial, mercantile) | - | - |
| 70 | Urban built-up (open trees / bush) | | | |
| 71 | Urban built-up (low veg / grass) | | | |
| 72 | Urban built-up (bare) | | | |

# 14. APPENDIX E: NATURAL LAND COVER CLASSES OF THE NLC 2000 DATABASE

This chapter investigates the distribution of the NLC 2000 natural land cover classes, and how and which individual final *ACRU* land cover classes (Table 11.1) have been assigned to each class, as summarised in Table 12.1. The distribution of the natural land cover classes from the NLC 2000 database was used with the Acocks (1988) natural land cover map, in order to identify the most appropriate Acocks land cover class to use to represent each of the NLC 2000 and NLC 2013/2014 natural land cover classes in the *ACRU* model. A representative Acocks (1988) natural land cover class was required in order to parameterise the *ACRU* model for each natural land cover class defined in the NLC classification. The Acocks (1988) natural land cover classes were used since these classes are the default "baseline" hydrological land cover classes assigned in the *ACRU* model to represent natural vegetation. Consequently, these land cover classes have been parameterised and verified for use with the *ACRU* model. Since the natural land cover classes of the NLC 2000 and NLC 2013/2014 databases are the same, the same classes assigned to the NLC 2000 natural land cover classes were assigned to the NLC 2013/2014 natural land cover classes for consistency. At the onset it is important to highlight that when assigning default final *ACRU* land cover classes to the NLC 2000 land cover classes, a degree of conservatism was applied, i.e. to rather overestimate than underestimate streamflow. Therefore, when assigning default classes, classes in fair condition or classes with intermediate stormflow potential were used. The user, however, may change the class if more detailed site-specific information is available.

Land cover class 1: Forest - Indigenous

This class is found mostly on the east coast and eastern interior of South Africa, as depicted in Figure 14.1, highlighted in blue. The final *ACRU* land cover class (Table 11.1) selected to represent this NLC 2000 class is Forests & Plantations, Humus depth 50 - 100mm - equivalent to intermediate trees (4-6 years Gum + Wattle + General; 6-11 years pine): Compactness/site preparation: Fair/Intermediate site prep (Table 12.1). This land cover class, taken from the revised SCS-SA land cover classification (Table 10.1), has the same *CN* values, translated into *ACRU QFRESP* and *SMDDEP* parameter values (Table 11.1), as that of the original SCS-SA Forests & Plantations classes (Schulze *et al.*, 2004), however, the names or explanations of the original treatment and hydrological condition classes have been revised and the classes simplified, *i.e.* in the original SCS-SA classification (Schulze *et al.*, 2004) there are three hydrological condition classes for a total of four treatment classes based on humus depth (25mm, 50mm, 100mm and 150mm). In the revised SCS-SA classification, however, the treatment classes have been reduced to three, however, still based on humus depth (<50mm, 50-100mm and >100mm). This revision was performed in order to link the classification of young, intermediate and mature forestry classes in the *ACRU* model to representative SCS-SA humus depth classes, i.e. assuming that humus depth is related to plantation / forest age. Therefore young, intermediate and mature trees was included with the humus depth classes in the final *ACRU* land cover classification. The revised <50mm class has the same *CN* values, translated into *ACRU QFRESP* and *SMDDEP* parameter values, as the original SCS-SA 25mm class, and the revised >100mm class has the same values as the original SCS-SA 150mm class. The revised 50-100mm class, however, combines the values from the original SCS-SA 50mm and 100mm classes and averages them into one representative class and set of *CN* and *QFRESP* and *SMDDEP* parameter values. Each treatment class still has three hydrological condition classes, however, also with updated nomenclature (Table 10.1 and Table 11.1), i.e. to accommodate forestry management practices as represented in the *ACRU* land cover classification for plantations. This includes (i) intensive site preparation, which is assumed to be equivalent to a compact hydrological condition as classified in the original SCS-SA classification (Schulze *et al.*, 2004), (ii) intermediate site preparation, which is assumed to be equivalent to a fair hydrological condition as classified in the original SCS-SA classification (Schulze *et al.*, 2004), and (iii) site preparation using pitting (site prep pitting), which is assumed to be equivalent to a loose or friable hydrological condition as classified in the original SCS-SA classification (Schulze *et al.*, 2004). The default *ACRU* land cover class assigned to this revised SCS-SA land cover class is FOREST / NATURAL FOREST, Compoveg number 5020101 (Table 10.1).

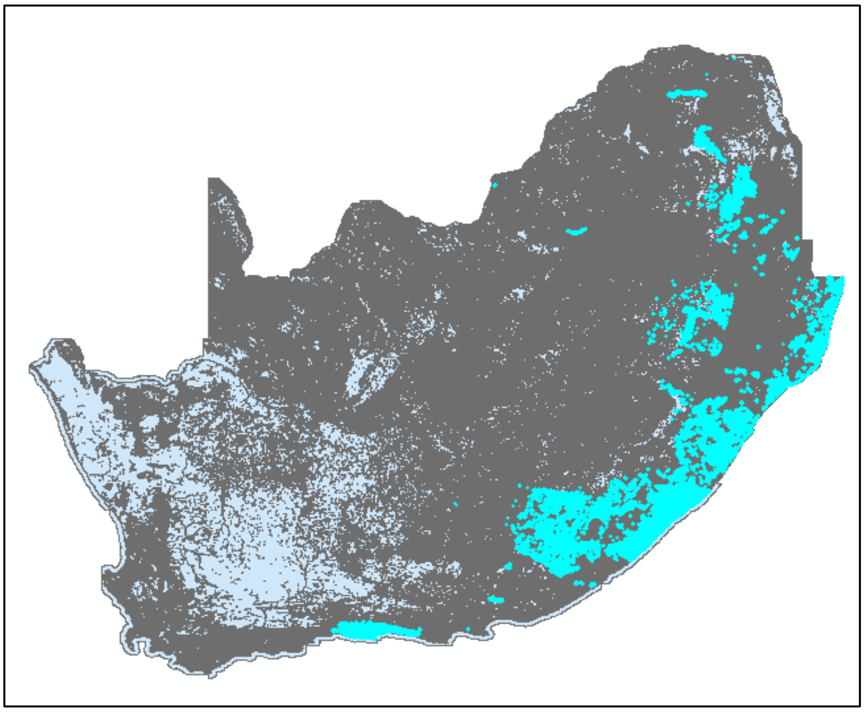

Figure 14.1 Forest - Indigenous (NLC 2000 Class 1)

Land cover class 2: Woodland - previously termed Forest and Woodland

This class is found mostly in northern South Africa, as depicted in Figure 14.2, highlighted in blue. The final *ACRU* land cover class (Table 11.1) selected to represent this NLC 2000 class is Woodland, in fair condition (Table 12.1). This land cover class, taken from the revised SCS-SA land cover classification (Table 10.1), has the same *CN* values, translated into *ACRU QFRESP* and *SMDDEP* parameter values (Table 11.1), as that of the original SCS-SA Woods and Scrub land cover class (Schulze *et al.*, 2004), however, classified as its own class called Woodland, and removing treatment class 4: Brush - Winter rainfall region Low. Consequently, the original SCS-SA Woods and Scrub land cover class (Schulze *et al.*, 2004) has been replaced with a class called Woodland (Table 10.1 and Table 11.1). The default *ACRU* land cover class assigned to this revised SCS-SA land cover class is WOODLAND (Indigenous/Tree-bush savannah), Compoveg number 2010101 (Table 10.1).

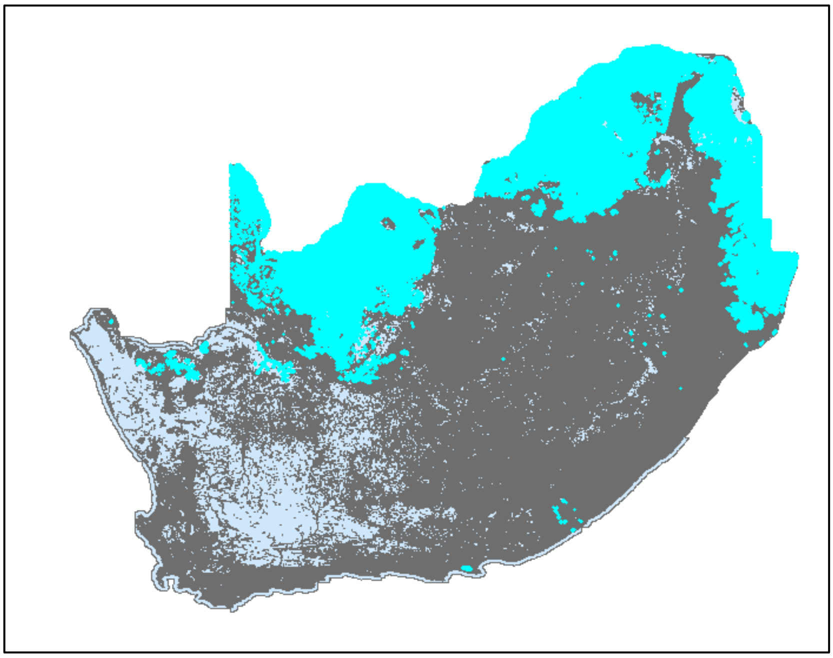

Figure 14.2 Woodland - previously termed Forest and Woodland (NLC 2000 Class 2)

Land cover class 3: Thicket, Bushland, Bush Clumps, High Fynbos

This land cover class is found extensively throughout South Africa, as depicted in Figure 14.3, highlighted in blue.

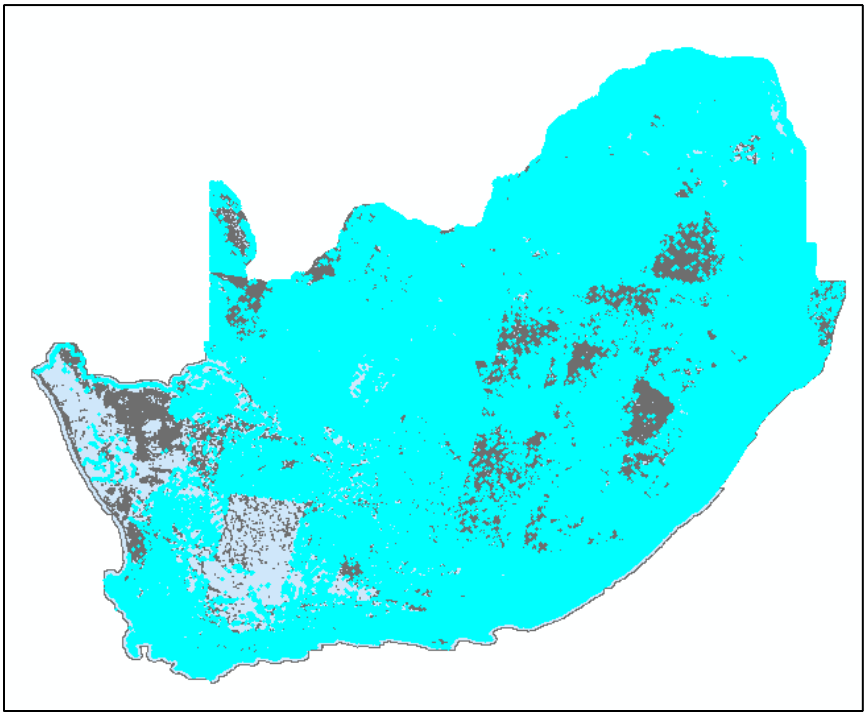

Figure 14.3 Thicket, Bushland, Bush Clumps, High Fynbos (NLC 2000 Class 3)

The final *ACRU* land cover class (Table 11.1) selected to represent this NLC 2000 class is Thicket, Bushland, Bush Clumps, High Fynbos, in fair condition (Table 12.1). This land cover class, taken from the revised SCS-SA land cover classification (Table 10.1), has the same *CN* values, translated into *ACRU QFRESP* and *SMDDEP* parameter values (Table 11.1), as that of the original SCS-SA Woods and Scrub land cover class (Schulze *et al.*, 2004), however, classified as its own class called Thicket, Bushland, Bush Clumps, High Fynbos, and once again removing treatment class 4: Brush - Winter rainfall region Low. Consequently, this revised SCS-SA land cover class is the same as the revised Woodland class described above, however, explicitly represents Thicket, Bushland, Bush Clumps, High Fynbos, and has its own default assigned *ACRU* land cover class. The default *ACRU* land cover class assigned to this revised SCS-SA land cover class is THICKET AND BUSHLAND etc., Compoveg number 5030101 (Table 10.1).

Land cover class 4: Shrubland and Low Fynbos

This class is mostly found in the western part of South Africa where it is typically a dominant land cover, as depicted in Figure 14.4, highlighted in blue.

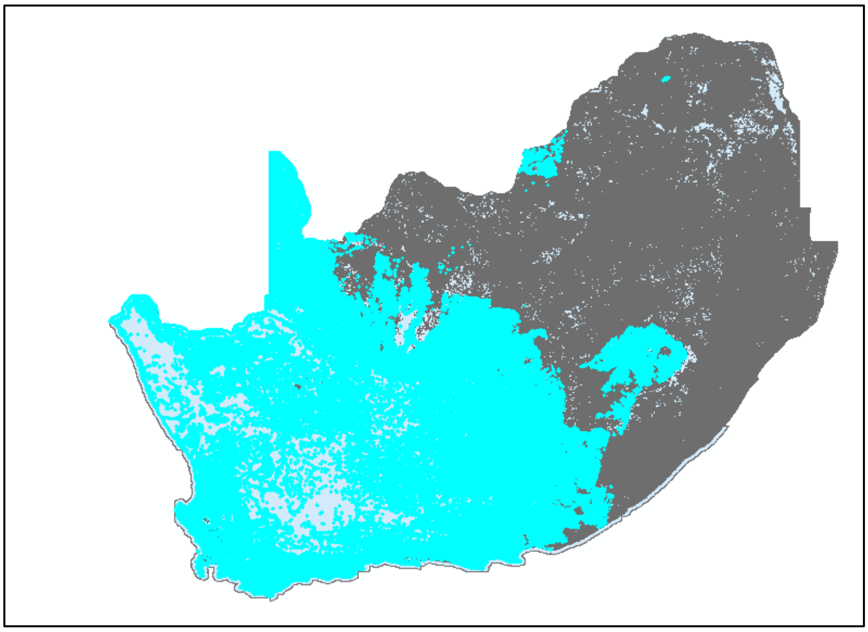

Figure 14.4 Shrubland and Low Fynbos (NLC 2000 Class 4)

The final *ACRU* land cover class (Table 11.1) selected to represent this NLC 2000 class is Shrubland and Low Fynbos, in fair condition (Table 12.1). This land cover class, taken from the revised SCS-SA land cover classification (Table 10.1), has the same *CN* values, translated into *ACRU QFRESP* and *SMDDEP* parameter values (Table 11.1), as that of the original SCS-SA veld / pasture treatment classes within the Veld (range) and Pasture land cover class (Schulze *et al.*, 2004), however, classified as its own class called Shrubland and Low Fynbos. Consequently, this revised SCS-SA land cover class is the same as the revised Unimproved (Natural) Grassland class described above, however, explicitly represents Shrubland and Low Fynbos, and has its own default assigned *ACRU* land cover class. Without an explicit *ACRU* land cover class, *i.e.* from Compoveg, to represent this NLC 2000 class, the Acocks (1988) natural land cover map was used to identify which Acocks land cover class is most representative of this NLC 2000 class, *i.e.* which Acocks class dominates the area highlighted in blue in Figure 14.4. Investigation identified the KARROID BROKEN VELD (Acocks #26), Compoveg number 2040104, as the most representative Acocks land cover class, and this class was assigned to the SCS-SA Shrubland and Low Fynbos class, i.e. as the default *ACRU* land cover class (Table 10.1).

Land cover class 5: Herbland

This class makes up a very small area of the North Western tip of South Africa, as depicted in Figure 14.5, highlighted in blue.

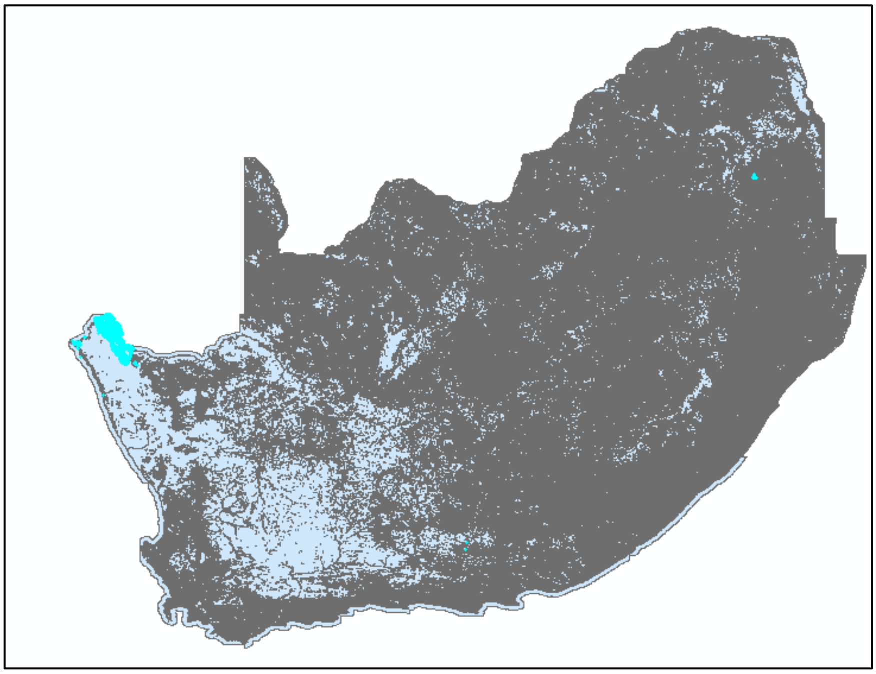

Figure 14.5 Herbland (NLC 2000 Class 5)

The final *ACRU* land cover class (Table 11.1) selected to represent this NLC 2000 class is Herbland, in fair condition (Table 12.1). This land cover class, taken from the revised SCS-SA land cover classification (Table 10.1), has the same *CN* values, translated into *ACRU QFRESP* and *SMDDEP* parameter values (Table 11.1), as that of the original SCS-SA veld / pasture treatment classes within the Veld (range) and Pasture land cover class (Schulze *et al.*, 2004), however, classified as its own class called Herbland. Consequently, this revised SCS-SA land cover class is the same as the revised Unimproved (Natural) Grassland, and Shrubland and Low Fynbos classes described above, however, explicitly represents Herbland, and has its own default assigned *ACRU* land cover class. Without an explicit *ACRU* land cover class, *i.e.* from Compoveg, to represent this NLC 2000 class, the Acocks (1988) natural land cover map was used to identify which Acocks land cover class is most representative of this NLC 2000 class, *i.e.* which Acocks class dominates the area highlighted in blue in Figure 14.5. Investigation identified THE WESTERN MOUNTAIN KAROO (Acocks #28), Compoveg number 2040106, as the most representative Acocks land cover class, and this class was assigned to the SCS-SA Herbland class, i.e. as the default *ACRU* land cover class (Table 10.1).

Land cover class 6: Unimproved (Natural) Grassland

This class is mostly found in and dominates the central and eastern parts of South Africa, as depicted in Figure 14.6, highlighted in blue. The final *ACRU* land cover class (Table 11.1) selected to represent this NLC 2000 class is Unimproved (Natural) Grassland, in fair condition (Table 12.1), and the default assigned *ACRU* land cover class is UNIMPROVED GRASSLAND, Compoveg number 5060103 (Table 10.1), *i.e.* as assigned to Class 0, which is assumed to be the same as this Unimproved (Natural) Grassland land cover class.

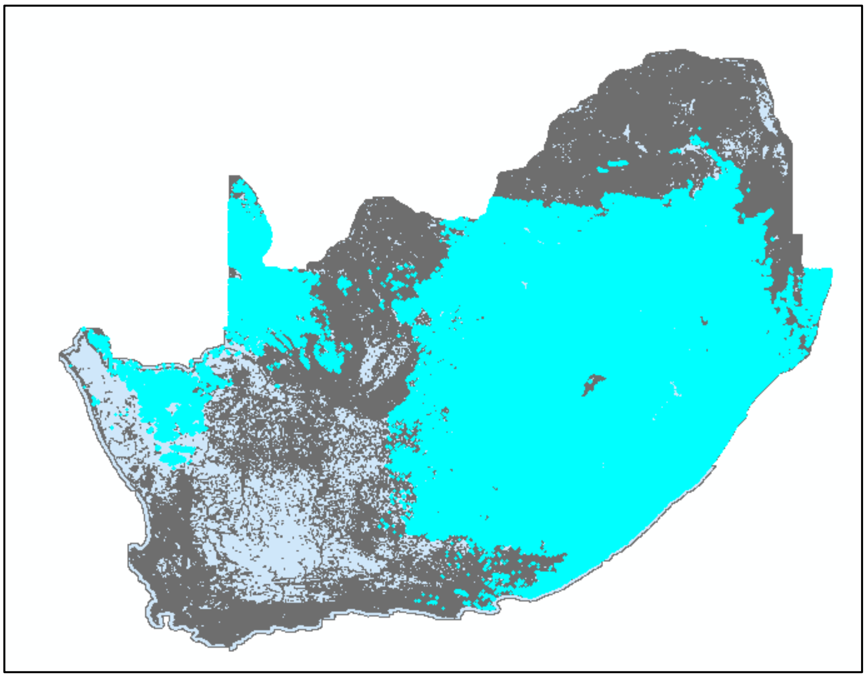

Figure 14.6 Unimproved (Natural) Grassland (NLC 2000 Class 6)

The remaining NLC 2000 and NLC 2013/2014 land cover classes were assigned SCS-SA and *ACRU* classes in a similar manner, and based on the rules and suggestions of Schulze (2013), as detailed in Section 3.3.2.

# 15. APPENDIX F: CSM SYSTEM AND DEFAULT *ACRU* MODEL STATISTICAL RESULTS FOR ALL CATCHMENTS USED IN VERIFICATION STUDIES

Table 15.1 Simulated versus observed NSE, RSQ and Slope values obtained for both the CSM system and the default implementation of the *ACRU* model, for both daily streamflow volumes and daily peak discharges

| Catchment | Area ($km^2$) | Daily Streamflow Volumes | | | | | | Daily Peak Discharges | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | CSM System | | | Default *ACRU* | | | CSM System | | | | | | Default *ACRU* | | | | | |
| | | NSE | RSQ | Slope | NSE | RSQ | Slope | NSE Current | RSQ Current | Slope Current | NSE Revised | RSQ Revised | Slope Revised | NSE Current | RSQ Current | Slope Current | NSE Revised | RSQ Revised | Slope Revised |
| **U2H020** | 0.26 | 0.86 | 0.87 | 0.83 | 0.66 | 0.67 | 0.61 | -8.08 | 0.32 | 1.96 | -1.89 | 0.33 | 1.18 | -12.17 | 0.35 | 2.44 | -0.08 | 0.36 | 0.75 |
| **V7H003** | 0.52 | 0.45 | 0.47 | 0.37 | 0.38 | 0.53 | 0.25 | -1.54 | 0.27 | 0.97 | -1.12 | 0.27 | 0.89 | -1.63 | 0.27 | 0.98 | 0.27 | 0.28 | 0.31 |
| **G2H010** | 0.73 | -3.44 | 0.54 | 1.86 | -4.20 | 0.61 | 2.12 | -277.66 | 0.21 | 7.79 | -23.70 | 0.30 | 2.97 | -925.05 | 0.32 | 17.50 | -80.67 | 0.39 | 5.98 |
| **V1H005** | 0.98 | 0.76 | 0.77 | 0.89 | 0.81 | 0.82 | 0.88 | -92.29 | 0.22 | 4.71 | -10.53 | 0.26 | 1.92 | -92.59 | 0.23 | 4.80 | -6.99 | 0.26 | 1.62 |
| **V1H015** | 1.04 | 0.66 | 0.69 | 0.73 | 0.63 | 0.66 | 0.56 | -6.73 | 0.46 | 2.27 | -1.24 | 0.47 | 1.36 | -5.26 | 0.44 | 2.03 | 0.40 | 0.46 | 0.63 |
| **U2H018** | 1.31 | 0.72 | 0.75 | 0.89 | 0.67 | 0.74 | 0.97 | -152.21 | 0.55 | 9.69 | -10.02 | 0.61 | 3.14 | -196.72 | 0.55 | 10.97 | -13.67 | 0.61 | 3.55 |
| **W1H016** | 3.30 | 0.56 | 0.78 | 1.16 | 0.61 | 0.64 | 0.73 | -5.59 | 0.62 | 2.56 | -0.70 | 0.66 | 1.61 | -4.20 | 0.61 | 2.32 | 0.67 | 0.68 | 0.79 |
| **X2H026** | 13.82 | -0.01 | 0.55 | 1.10 | -0.18 | 0.52 | 1.12 | -56.87 | 0.15 | 3.07 | -6.57 | 0.20 | 1.34 | -122.93 | 0.17 | 4.73 | -6.94 | 0.22 | 1.48 |
| **A9H006** | 16.00 | 0.42 | 0.52 | 0.74 | 0.44 | 0.52 | 0.71 | -15.54 | 0.18 | 1.87 | -1.43 | 0.28 | 0.98 | -21.92 | 0.19 | 2.24 | -0.97 | 0.31 | 0.94 |
| **V1H032** | 67.80 | 0.10 | 0.44 | 0.75 | 0.29 | 0.41 | 0.49 | 0.06 | 0.34 | 0.64 | 0.17 | 0.34 | 0.57 | 0.20 | 0.35 | 0.57 | 0.28 | 0.35 | 0.19 |
| **X2H027** | 77.16 | 0.02 | 0.49 | 0.97 | -0.19 | 0.45 | 0.98 | -34.14 | 0.11 | 2.01 | -3.91 | 0.24 | 1.23 | -86.90 | 0.12 | 3.29 | -8.01 | 0.23 | 1.61 |

Table 15.2 Simulated versus observed MARE and MRE values obtained for both the CSM system and the default implementation of the *ACRU* model, for both design streamflow volumes and design peak discharges

| **Catchment** | **Area ($km^2$)** | **Design Streamflow Volumes** | | | | **Design Peak Discharges** | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | **CSM System** | | **Default *ACRU*** | | **CSM System** | | | | **Default *ACRU*** | | | |
| | | **MARE** | **MRE** | **MARE** | **MRE** | **MARE Current** | **MRE Current** | **MARE Revised** | **MRE Revised** | **MARE Current** | **MRE Current** | **MARE Revised** | **MRE Revised** |
| **U2H020** | 0.26 | 0.19 | 0.12 | 0.21 | -0.11 | 1.80 | 1.80 | 0.66 | 0.66 | 2.55 | 2.55 | 0.18 | 0.08 |
| **V7H003** | 0.52 | 0.22 | -0.22 | 0.66 | -0.66 | 1.84 | 1.84 | 1.59 | 1.59 | 1.96 | 1.96 | 0.23 | -0.08 |
| **G2H010** | 0.73 | 0.60 | 0.60 | 1.06 | 1.06 | 29.55 | 29.55 | 8.31 | 8.31 | 48.63 | 48.63 | 14.08 | 14.08 |
| **V1H005** | 0.98 | 0.11 | 0.09 | 0.10 | -0.03 | 8.73 | 8.73 | 2.62 | 2.62 | 8.62 | 8.62 | 1.91 | 1.91 |
| **V1H015** | 1.04 | 0.06 | 0.04 | 0.42 | -0.42 | 3.87 | 3.87 | 1.89 | 1.89 | 3.63 | 3.63 | 0.42 | 0.41 |
| **U2H018** | 1.31 | 0.09 | -0.09 | 0.13 | 0.13 | 10.70 | 10.70 | 2.56 | 2.56 | 14.25 | 14.25 | 3.64 | 3.64 |
| **W1H016** | 3.30 | 0.31 | 0.29 | 0.34 | -0.34 | 2.46 | 2.46 | 1.06 | 1.06 | 2.17 | 2.17 | 0.26 | -0.01 |
| **X2H026** | 13.82 | 0.61 | 0.61 | 0.65 | 0.65 | 7.68 | 7.68 | 2.25 | 2.25 | 10.07 | 10.07 | 2.12 | 2.12 |
| **A9H006** | 16.00 | 0.31 | 0.18 | 0.29 | 0.04 | 5.21 | 5.21 | 1.46 | 1.46 | 5.82 | 5.82 | 1.09 | 1.09 |
| **V1H032** | 67.80 | 0.23 | 0.00 | 0.58 | -0.58 | 0.08 | 0.07 | 0.09 | -0.04 | 0.09 | -0.01 | 0.69 | -0.69 |
| **X2H027** | 77.16 | 0.37 | 0.37 | 0.50 | 0.50 | 10.80 | 10.80 | 3.46 | 3.46 | 14.75 | 14.75 | 4.40 | 4.40 |

# 16. APPENDIX G: COMPARATIVE PLOTS OF DESIGN STREAMFLOW / STORMFLOW VOLUMES AND DESIGN PEAK DISCHARGES SIMULATED BY THE CSM SYSTEM AND SCS-SA MODEL PER VERIFICATION CATCHMENT

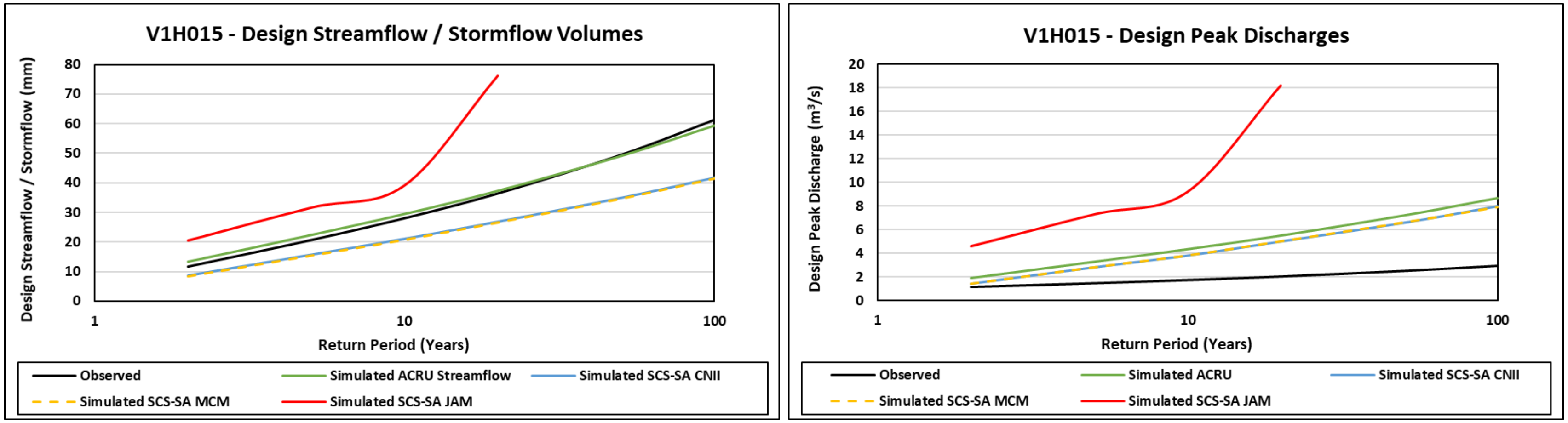

Figure 16.1 Observed and simulated design streamflow/stormflow volumes and design peak discharges for DeHoek/Ntabamhlope (V1H015), applying both the *ACRU* and SCS-SA models

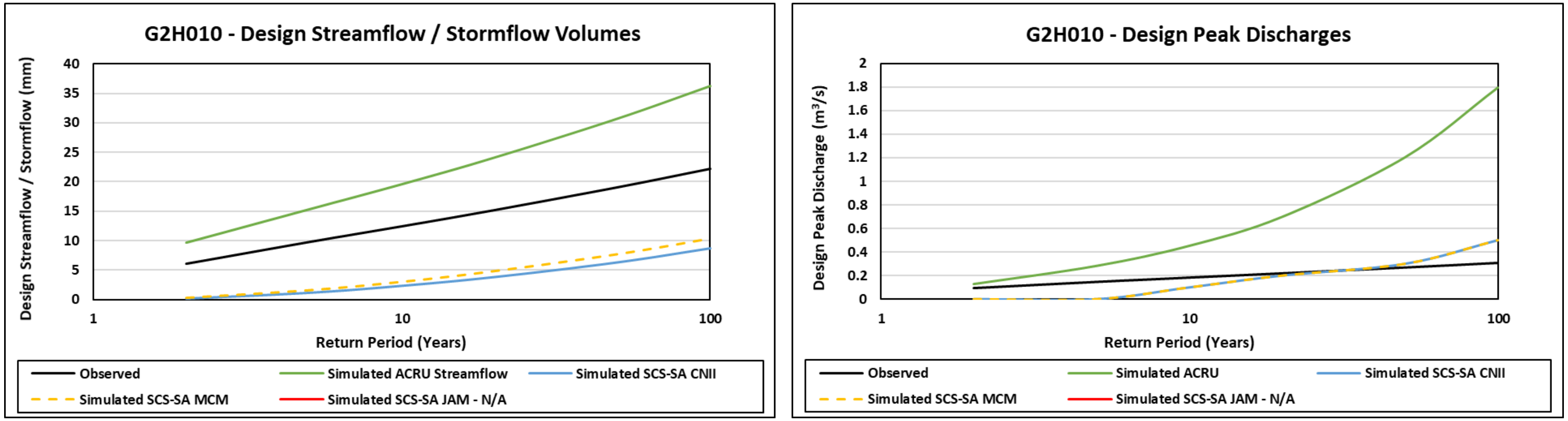

Figure 16.2 Observed and simulated design streamflow/stormflow volumes and design peak discharges for Lambrechtsbos B (G2H010), applying both the *ACRU* and SCS-SA models

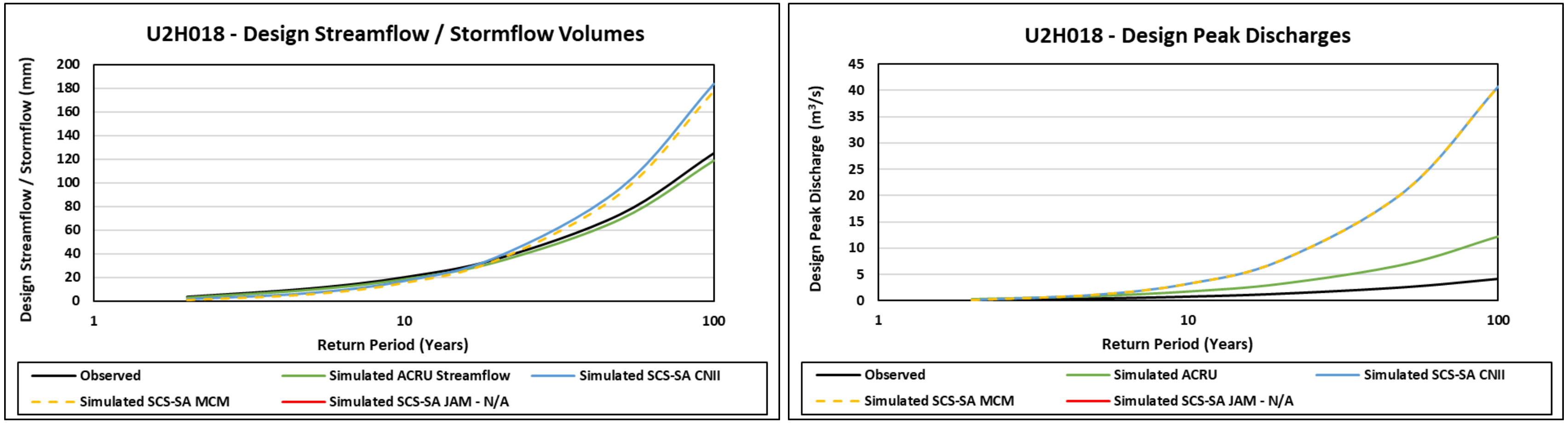

Figure 16.3 Observed and simulated design streamflow/stormflow volumes and design peak discharges for Cedara (U2H018), applying both the *ACRU* and SCS-SA models

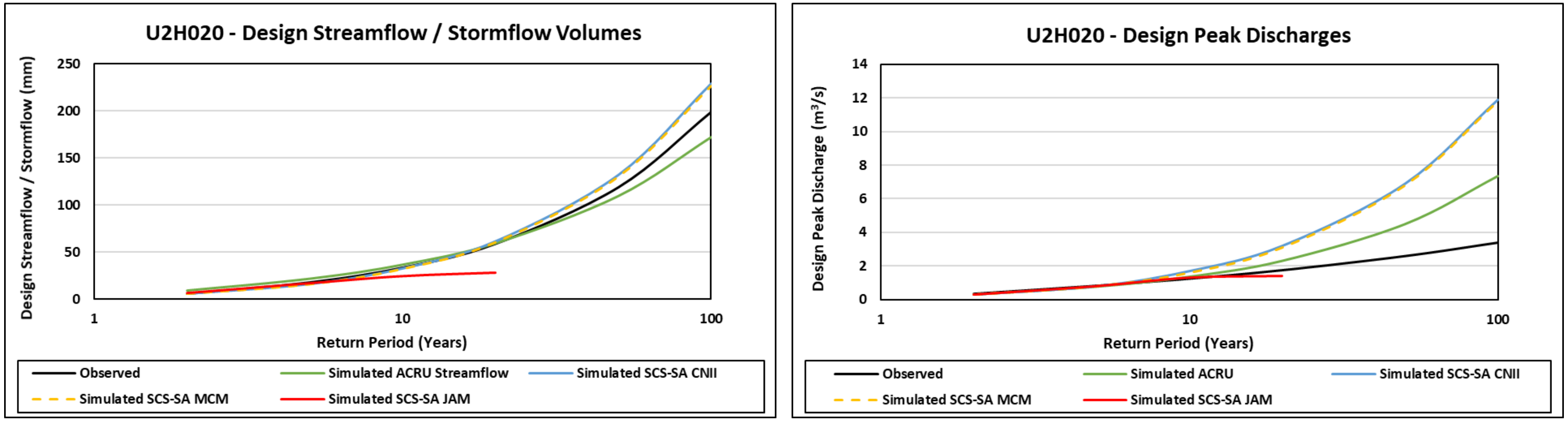

Figure 16.4 Observed and simulated design streamflow/stormflow volumes and design peak discharges for Cedara (U2H020), applying both the *ACRU* and SCS-SA models

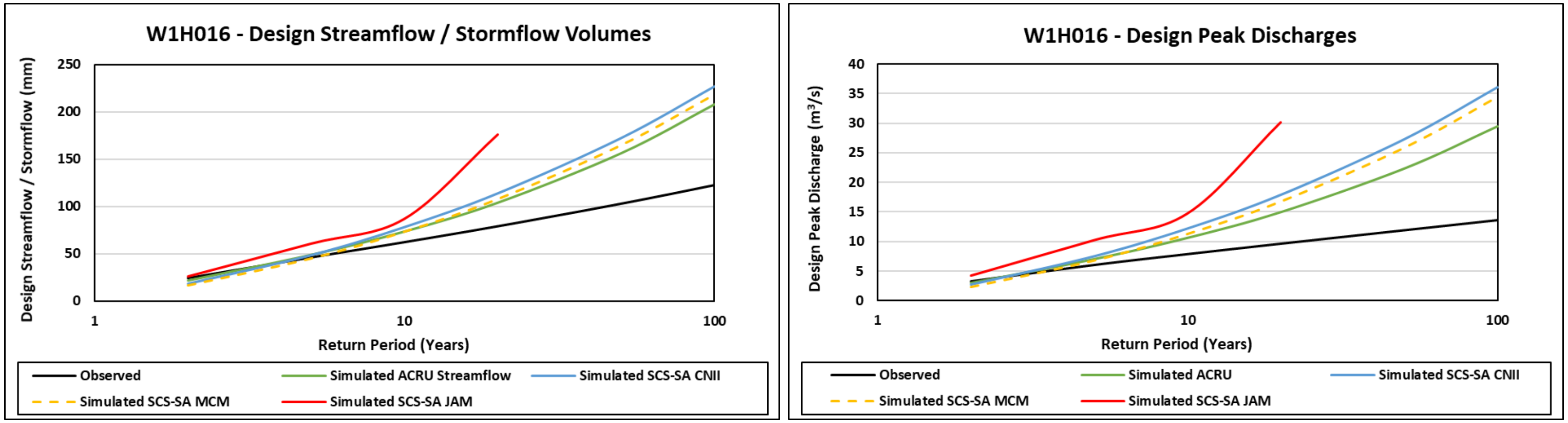

Figure 16.5 Observed and simulated design streamflow/stormflow volumes and design peak discharges for Zululand (W1H016), applying both the *ACRU* and SCS-SA models

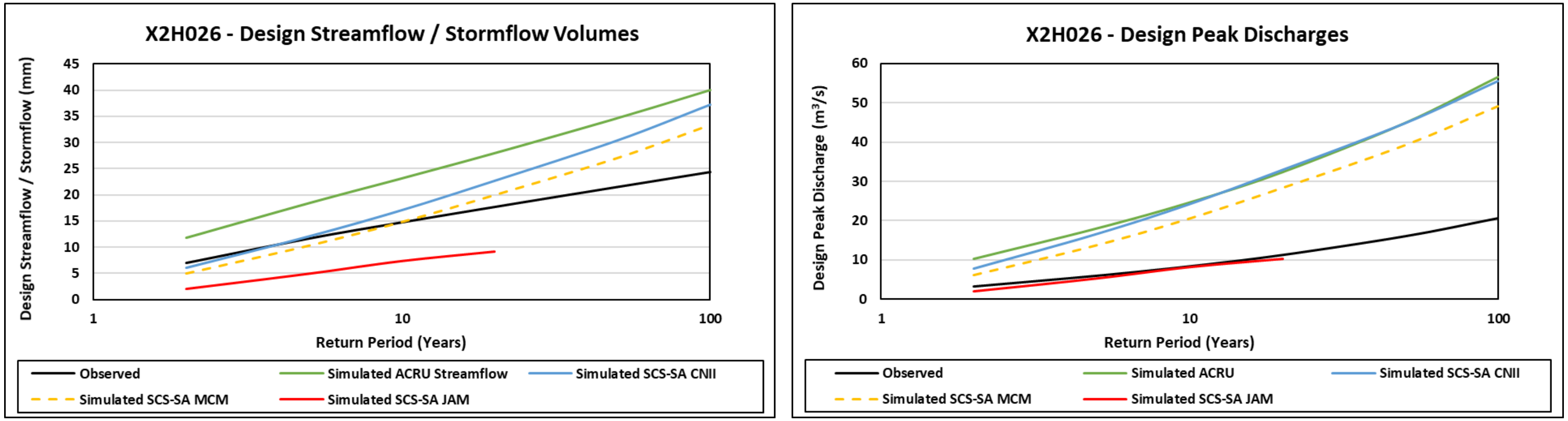

Figure 16.6 Observed and simulated design streamflow/stormflow volumes and design peak discharges for Catchment X2H026, applying both the *ACRU* and SCS-SA models

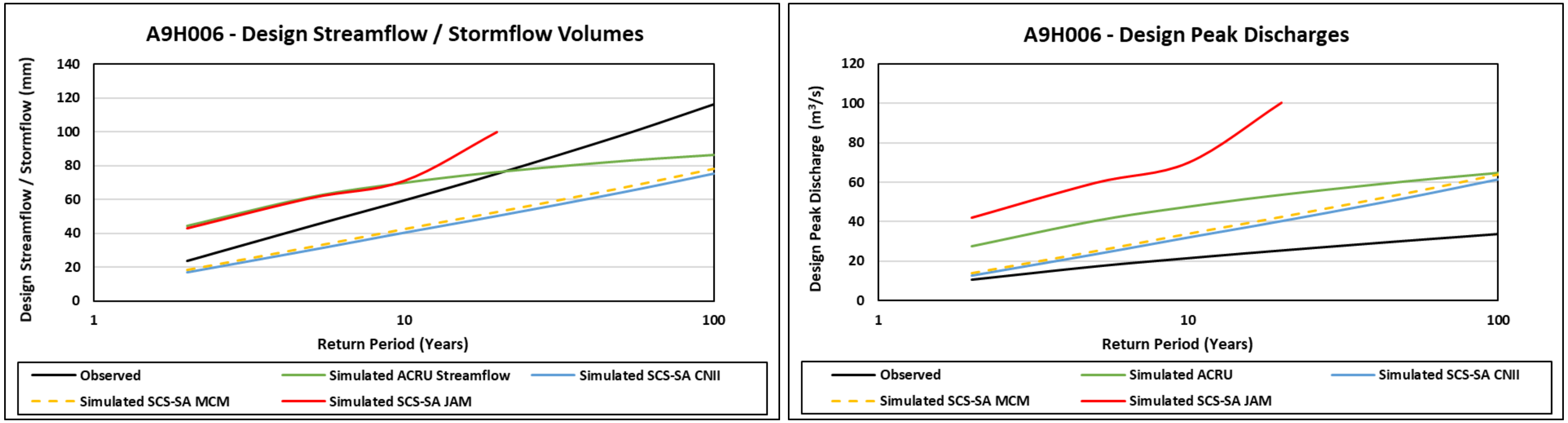

Figure 16.7 Observed and simulated design streamflow/stormflow volumes and design peak discharges for Catchment A9H006, applying both the *ACRU* and SCS-SA models

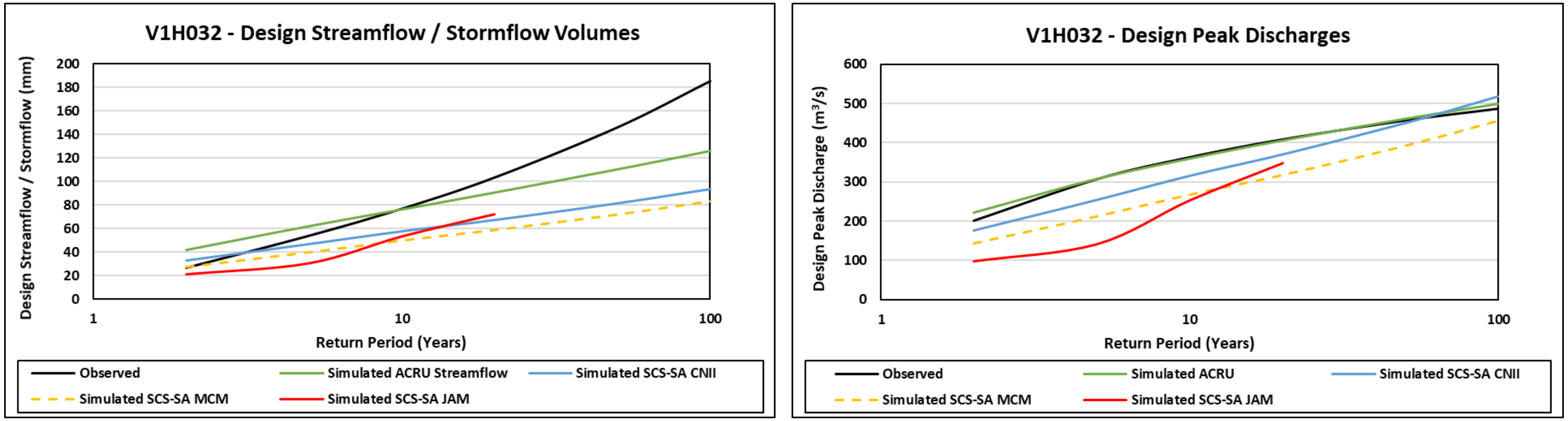

Figure 16.8 Observed and simulated design streamflow/stormflow volumes and design peak discharges for Catchment V1H032, applying both the *ACRU* and SCS-SA models

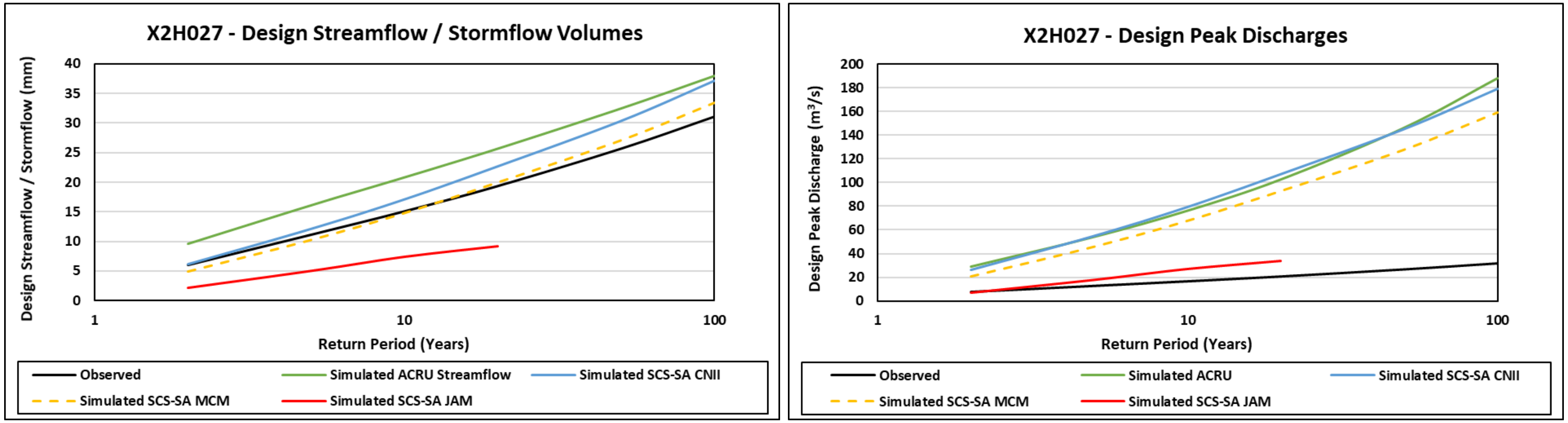

Figure 16.9 Observed and simulated design streamflow/stormflow volumes and design peak discharges for Catchment X2H027, applying both the *ACRU* and SCS-SA models